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A DIRECT DIGITAL NUMERICAL CONTROLLER FOR MACHINE TOOLS

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January 1975

MASTER

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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A DIRECT DIGITAL NUMERICAL CONTROLLER FOR MACHINE TOOLS

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ABSTRACT

A direct digital numerical controller (DDNC) was developed as an alternative to the current numerical control (NC) concept with the expectation of improving the performance and the design criteria for an NC controller.

The need for a DDNC was prompted by a program to decrease the time required for machining special, low-volume, custom-made parts.

DDNC offers several improvements over commerically available NC, such as: (1) magnetic core memory replacement of the tape reader during machining, (2) capability of remote loading via a high-speed transmission line from the computer, (3) part-description data stored in highly efficient binary format rather than EIA code, (4) size savings of 75% in required floor space with a significant reduction in circuit components and accompanying maintenance, and (5) greater than 50% cost savings. Full, five-axis, continuous-path contouring (using linear interpolation) is available on the DDNC with manual control features basically the same as those found on NC units.

DDNC units were installed on three Ex-Cell-O two-axis turning machines, and a number of parts were machined. DDNC proved to be a practical, economical, and reliable method for machine-tool control.

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SUMMARY

A direct digital numerical controller (DDNC) was developed as part of a program to decrease the time required for machining special, custom-made, low-volume parts at the Oak Ridge Y-12 Plant[a].

DDNC offers several improvements over commercially available numerical control (NC) units, such as:

1. Sufficient magnetic core memory is provided to store the entire part-description data so that tape-reader usage during machining is eliminated.

2. Part description data are loaded into the core memory via a high-speed transmission line from a computer.

3. Part description data are stored in memory with a highly efficient binary format instead of the standard EIA code.

4. The DDNC requires approximately 75% less floor space than NC units.

5. Less complex circuitry is required to implement the machine-tool control functions, resulting in a system more easily maintained.

6. For one particular machine-tool control application, a DDNC system costs $15,000, compared to $35,000 for comparable NC equipment.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

INTRODUCTION

A significant development effort over the last six years has involved the use of minicomputers for machine tool control.[1,2] From this work, an open-loop control concept was developed that utilizes a digital differential analyzer (DDA) for pulse-train generation and electrohydraulic pulse motors for axes drives. This method of controlling a machine tool was demonstrated to be both practical and reliable. Further development effort has resulted in replacing the minicomputer with a compact, hardwired controller and core memory for part description data storage.

Development of the DDNC was prompted by a need to decrease the time required for machining special, low-volume, custom-made parts. A significant portion of the turn-around time for machining these types of parts involved generating, verifying, and machine debugging NC part description tapes. The DDNC, with access to a central control computer (CCC), provides a system capable of significantly reducing this turnaround time.

A minicomputer-directed machine-tool control center generates part-description data from design data. These data are transmitted directly to a digital numerical control unit located at the machine tool.

DDNC units are connected to the CCC by a serial transmission line operating on a party-line basis. A complete part description is stored in core memory upon request from the machine-tool station, thus making the DDNC unit independent of the CCC after a load sequence.

THE DIRECT DIGITAL NUMERICAL CONTROLLER

REASONS FOR DIRECT DIGITAL NUMERICAL CONTROL

A continuing development effort, based on accomplishments made with regard to the computer-controlled Ex-Cell-O two-axis contouring machine,(1) a computer-controlled Monarch lathe,(2) and the provision of core memory part description storage for numerically controlled (NC) machine tools,(3) has resulted in the development of a direct digital numerical controller (DDNC).

The DDNC is connected to a minicomputer-directed, machine-tool control center. This central control computer (CCC), with the capability for real-time generation of part description data directly from design drawings, transmits a complete binary-formatted part description file to a DDNC upon request. Numerical controllers were replaced with DDNC units on three Ex-Cell-O two-axis turning machines (two 922 units and one 921T unit). A DDNC unit installed on an Ex-Cell-O 921T machine is seen in Figure 1.

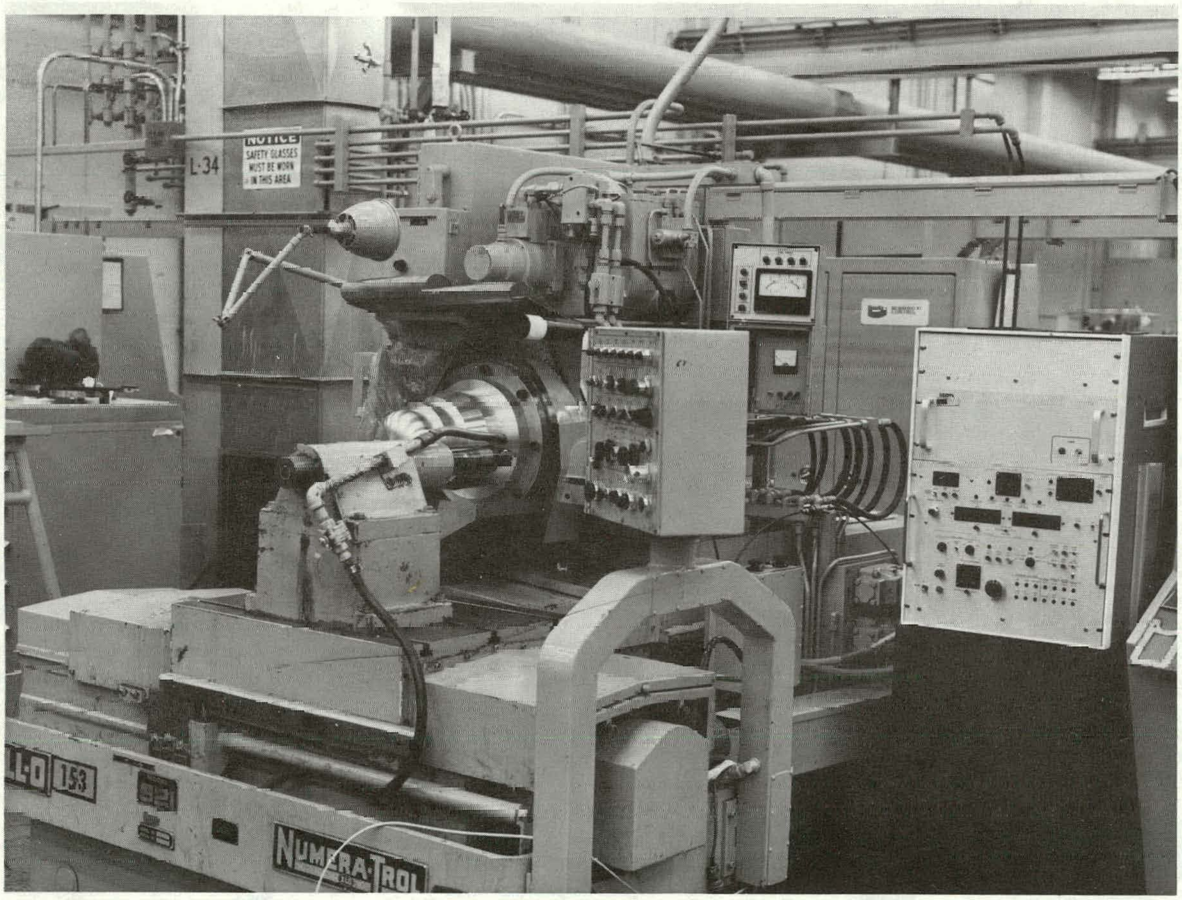

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Figure 1. EX-CELL-O MODEL 921T TURNING MACHINE WITH DIRECT DIGITAL NUMERICAL CONTROL.

DIRECT DIGITAL NUMERICAL CONTROL OPERATION

A block diagram of the DDNC is provided in Figure 2. Each DDNC unit is tied to the CCC by a transmission party line consisting of four twisted-pair lines. Part description data generated by the CCC are stored in the DDNC using two 8-kiloword (8-K) by 18-bit core memories addressed in parallel to obtain an 8-K by 36-bit configuration. Part description data are transmitted (bit serially) from the remotely located computer and strobbed into a 36-bit shift register. After one word is received, a parallel transfer stores the data word in core memory.

When the entire part description has been stored in core memory, the DDNC is ready for program execution and is independent of the CCC. Figure 3 illustrates the data-block format for the DDNC binary words. Axis distance (X, Y, Z, A, B), M function, sequence number (N), all codes (G, S, T), and feedrate number are coded, as shown. A data block for two-axis control will consist of from one to four words.

The equivalent of approximately 203 m (666 ft) of tape containing EIA Standard RS-274-B data can be stored in an 8-kiloword by 36-bit core memory when using the binary-format stacking scheme.

DDNC operates in the following manner:

1. Reads the binary part description data from core memory.

2. Decodes and then loads the binary data into the proper execute registers.

3. The digital differential analyzer generates a pulse train for movement of the axes.

4. Axes pulse trains are inputted to accelerator/decelerator circuitry to prevent rapid changes in the pulse rate.

5. Axes pulse trains are then converted into a five-phase signal by translator logic for the electrohydraulic pulse motors.

6. M, G, S, and T code functions are executed in the same manner as with NC.

Due to the binary organization of the part-description data, less complex circuitry is required to implement machine-tool control functions, resulting in a system more easily maintained. A comparison of the stacking density using binary-formatted data and EIA coded data is given in Appendix A.

When a "program execute" is initiated, a core memory read/restore cycle transfers one word into the 36-bit shift register of Figure 2. The three most significant bits (33, 34, 35) are then interrogated by the decoding logic to determine the binary-data destination. This data-transfer sequence continues until an end-of-block code (Bit 35 = 1) is detected. Succeeding data blocks are handled similarly. S, M, G, and T codes are executed in the same manner as with conventional NC units. Hardware interpolation by the digital differential analyzer generates a pulse train for the X and Y axes. This technique and the function of the accelerator/decelerator circuitry has been reported.[2]

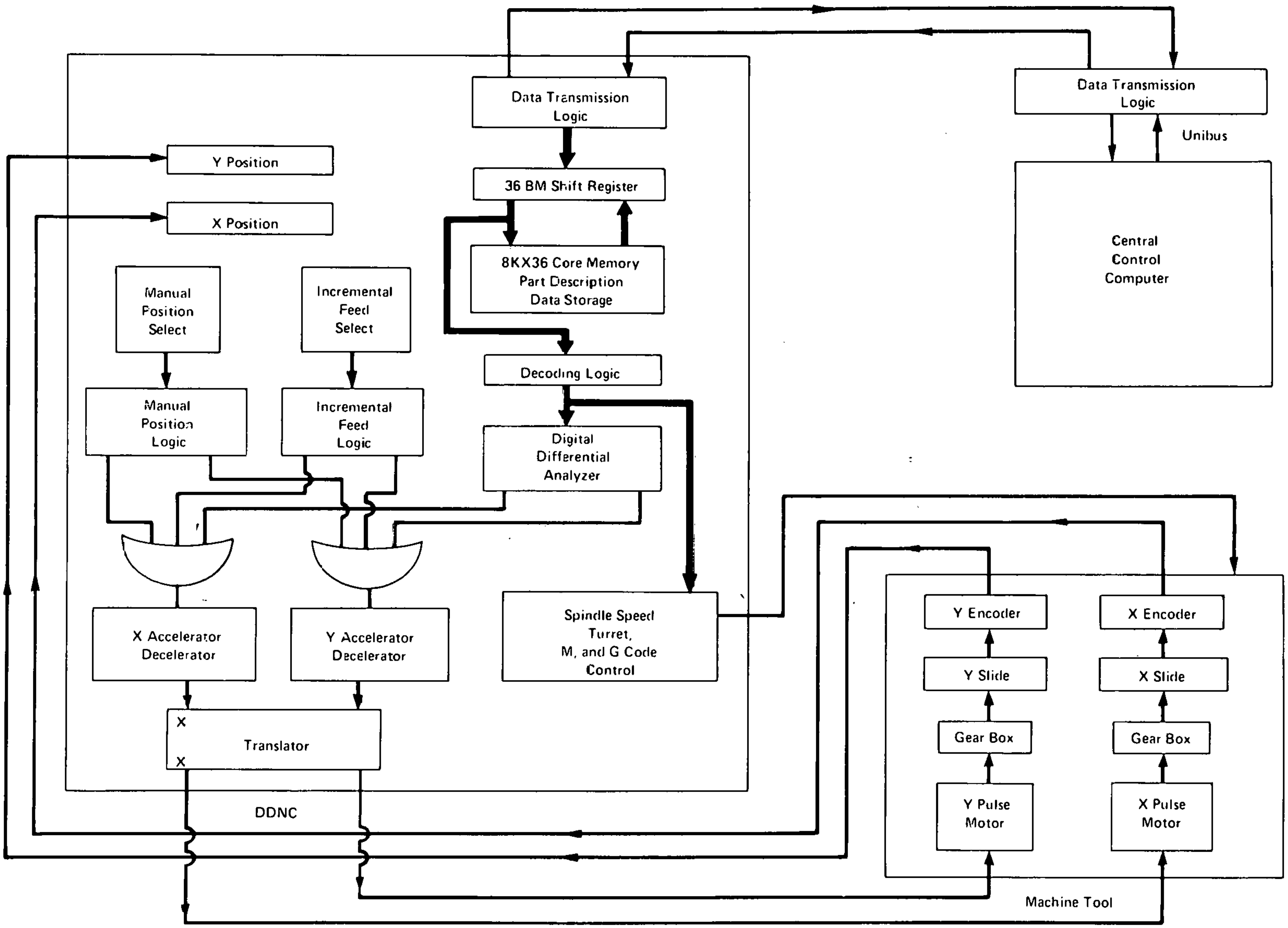

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Figure 2. PRINCIPAL COMPONENTS OF THE DIRECT DIGITAL NUMERICAL CONTROL UNIT.

35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0

ID Code	M Number		Not Used	X Distance with Sign and Marker Bit	Parity
0 0 1	10^0	10^1			
0 1 0					

Identification Code 001 - X Distance Only; 010 X Distance and M Function

ID Code	Not Used	Core Memory Address	Parity
0 0 0			

Identification Code 000 - Sequence Number

ID Code	G Code	S Code	T Code	Z Code	A Code	B Code	T Ident	T Code Number		S Code		G Code		Parity
0 1 1								10^0	10^1	10^0	10^1	10^0	10^1	

Identification Code 011 - Auxiliary Function

ID Code	Inverse Feedrate	Y Distance with Sign and Marker Bit	Parity
	$FR = \left\{\left[\frac{6 \times 10^8}{F}\right] \div 2^N\right\} \div 8$		

Identification Code 1 - End of Block, Y Distance, and Feedrate Number

155300

Figure 3. **DIRECT DIGITAL NUMERICAL CONTROLLER DATA FORMAT.**

As shown in Figure 2, the DDNC unit has two-axis control. Provisions were made in the DDNC circuitry to handle up to five axes. Detailed engineering drawings for the DDNC circuitry and the transmission logic are provided in Appendix B.

REMOTE LOADING OF DIRECT DIGITAL NUMERICAL CONTROLLER WITH PART DESCRIPTION DATA

Data words are transmitted bit serially over four twisted-pair lines, as indicated in Figure 4. With this method, the system operates in a balanced mode. Noise induced on one line appears on the other line and is rejected at the input of the receivers. Clock pulses are transmitted with each data word to shift the data bits into the receiver register.

DDNC data transmission operates in a party-line system, as noted in Figure 5. A view of the control panel is given in Figure 6. When it is necessary to load the DDNC, the operator loads the part description title number into the program-select switches and pushes the program-load button. The data word, shown in Figure 7, is then transmitted to the CCC. This word consists of the part description number, machine station identification number, parity bit, and skew bits.

After the data word is received by the CCC interface, a computer program interrupt is generated. The computer then strobes the data word into memory and checks the parity bit and skew bits. If these bits are correct, the part description number is used to locate the corresponding data file either on disk or magnetic tape. Detection of a skew-bit or parity-bit error terminates the load sequence, and a transmission-fault word is transmitted to the DDNC.

After the station is identified and the part description is located, data are transmitted from the CCC to the DDNC. Each 36-bit word is serially shifted into a storage register in the DDNC and then transferred to core memory. As each data word is received by the DDNC, a check is made for correct parity and location of the skew bits. If an error is detected during the transmission interval, a transmission "fault" light on the control panel indicates this condition.

"Fault" lights also notify the operator when the selected program cannot be found on file or if the computer is not available. With the transmission scheme operating on a party-line basis, it is possible that the transmission line will be busy loading another DDNC when an operator requests a program load. If this condition exists, a "busy" light comes on, and the operator must initiate the load sequence again. When the data transmission "active" light goes out and none of the "fault" lights are on, the operator can begin the machining operation.

SALIENT FEATURES OF DIRECT DIGITAL NUMERICAL CONTROL

Manual-control functions such as sequence search, feedrate override, jog, single pulse, incremental feed, optional stop, and cycle hold are provided by the DDNC. Every core memory location is accessible by means of the sequence-search feature. A desired memory location can be accessed by loading its address into the sequence-number switches and depressing the "sequence-search" button. Current core memory location is displayed in base octal by the program-address register.

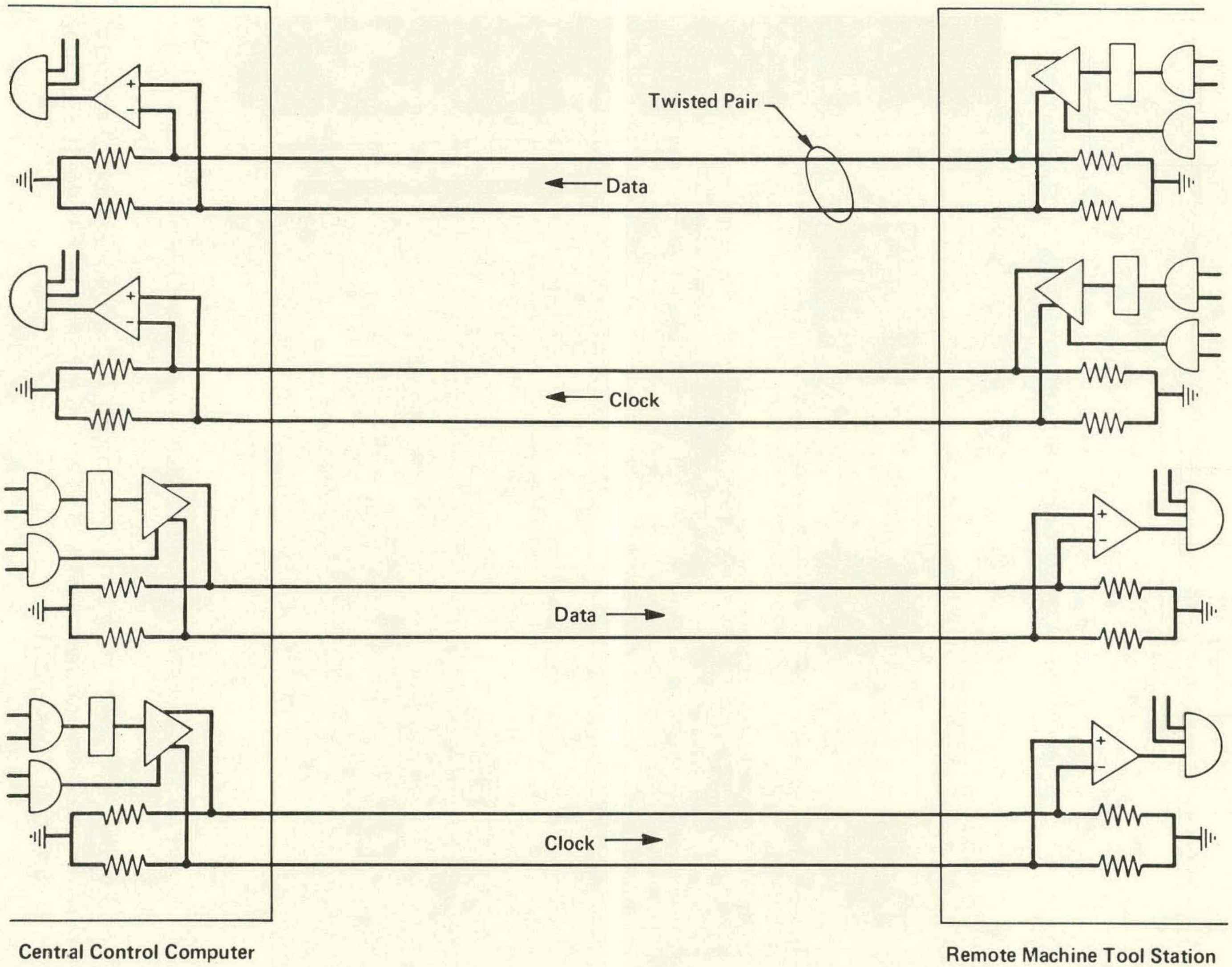

Figure 4. CIRCUITRY OF THE DATA TRANSMISSION SYSTEM.

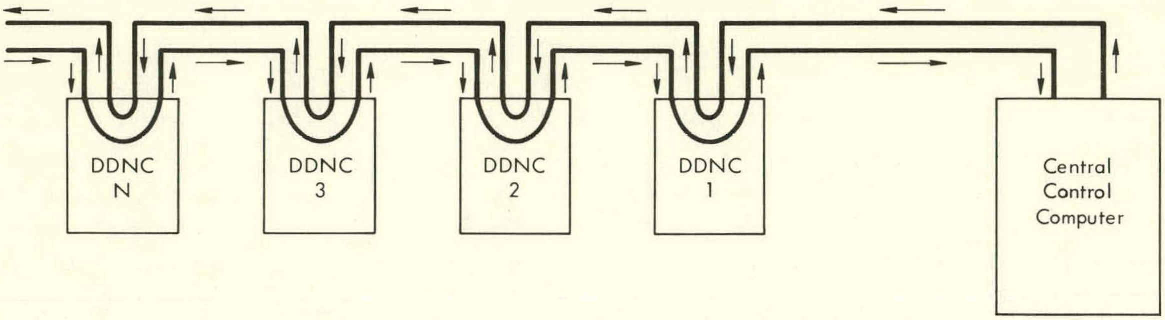

Figure 5. DATA TRANSMISSION PARTY-LINE SYSTEM.

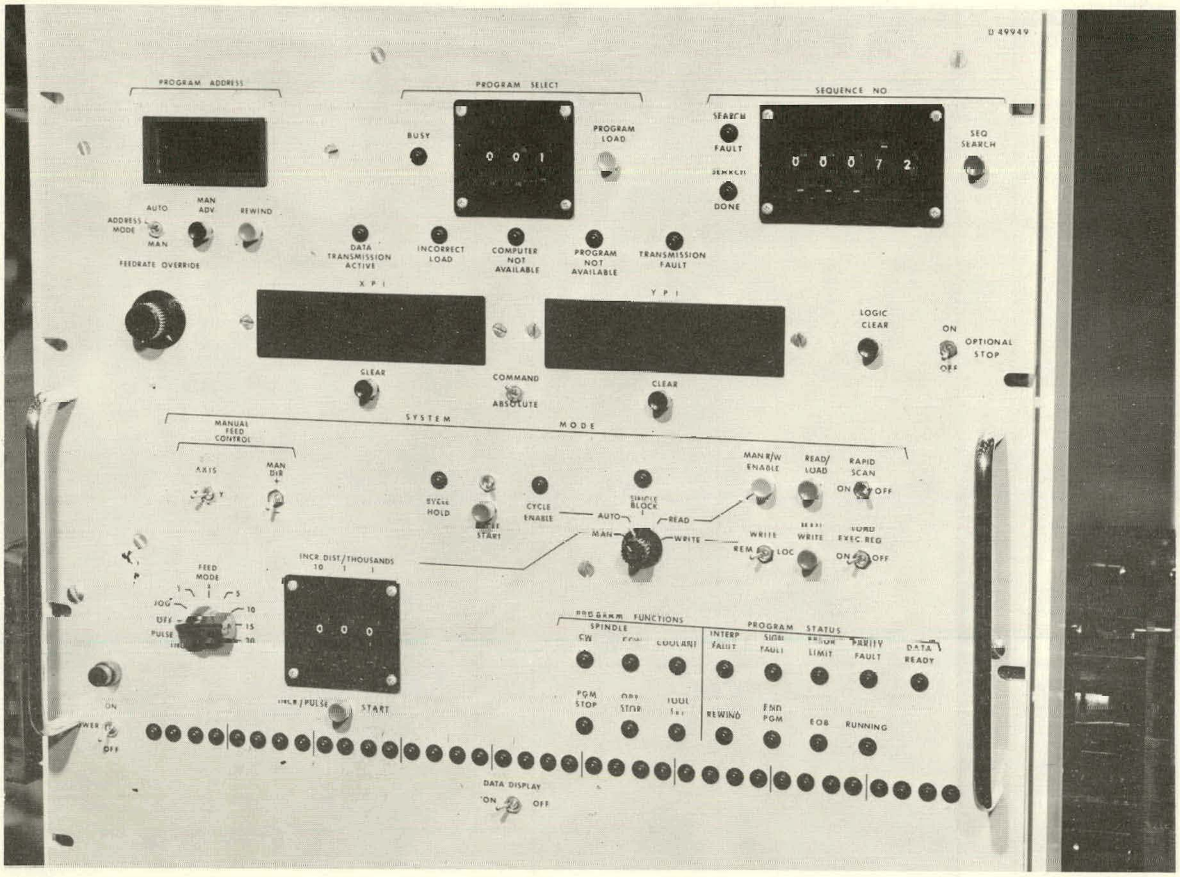

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Figure 6. DIRECT DIGITAL NUMERICAL CONTROLLER CONTROL PANEL.

Part description data are stored in core memory starting at Location O. From the control panel, data can be read from core and displayed by the 36 light-emitting diodes (LEDs) near the bottom of the control panel, as shown in Figure 6.

Electrohydraulic pulse motors (EHPMs), as seen in Figure 8, drive the X and Y slides. Gear modifications were made to provide a 20-microinch pulse resolution. Digital pulse trains generated by the digital differential analyzer are inputted to the accelerator/decelerator circuitry and then to the translator where a five-phase signal is generated for the pulse

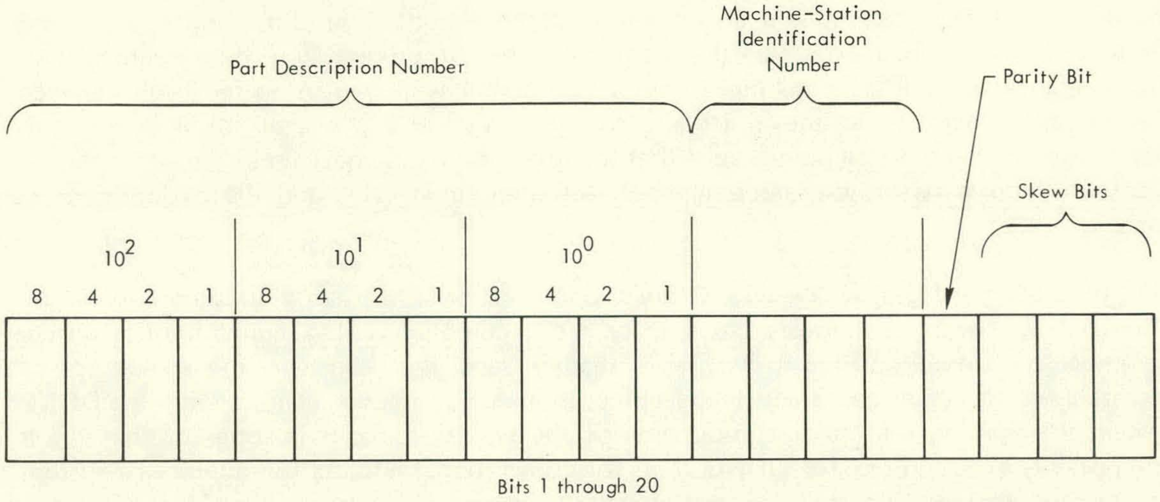

Figure 7. DATA WORD TRANSMITTED TO THE CENTRAL CONTROL COMPUTER.

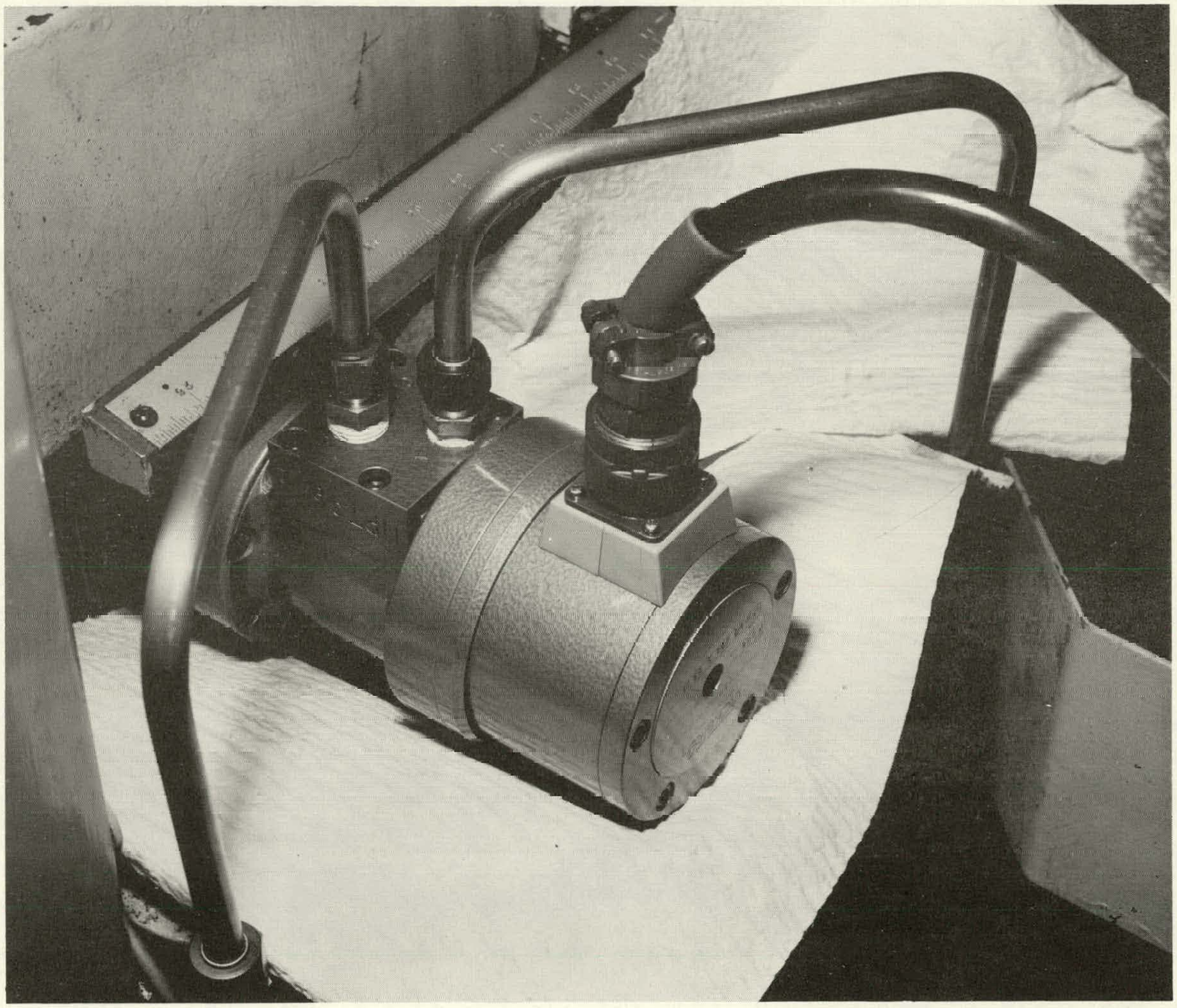

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Figure 8. ELECTROHYDRAULIC PULSE MOTOR.

motors. The system operates in an open-loop control mode. The term "digital open-loop control" is used here to describe a system composed of a digital controller coupled with digital actuators (EHPMs), making a completely digital system with no feedback between the controlled member and the controller. However, to avoid any misconception of the term "open loop", it should be pointed out that the pulse motors do have an internal mechanical feedback loop between the stepping-motor-actuated servo valve and the hydraulic drive motor.

One of the advantages of the DDNC open-loop control is, primarily its simplicity in the all-digital approach as opposed to the far more complex analog/digital hydrid system common to closed-loop controls. It is readily seen that the two major sources of maintenance (ie, tape reader and feedback components) have been eliminated in the DDNC system. Comparing the major components of the two systems, it is apparent that fewer components are required for DDNC than for conventional NC. As the number of system components increases, the failure rate generally increases.

Cost and installation comparison of the two systems also follow the previously described relationship (ie, simpler interface and lower initial cost). Table 1 presents a cost comparison between DDNC and NC.

Table 1

COST COMPARISON BETWEEN DIRECT DIGITAL NUMERICAL CONTROL AND NUMERICAL CONTROL

Direct Digital Numerical Control		Numerical Control	
Parts	$9,700	Purchase	$35,000
cation Labor	2,500		
kout	2,000		
Totals	$14,200		$35,000

Advantages of DDNC compared to NC can be summarized as follows:

1. Retains the manual controls from NC and yet expands the sequence search capability and ability to visually examine part description data.

2. Eliminates the tape reader with part description data being stored in core memory.

3. Digital open-loop control eliminates analog conversion problems and complex feedback circuitry.

4. Less maintenance required for the DDNC due to the reduced complexity of the control circuitry.

5. Lower fabrication cost and checkout cost for DDNC than purchase cost for NC.

6. DDNC units are interchangeable.

7. A number of DDNC units can be tied to the CCC.

8. After a DDNC station is loaded with part description data, it is independent of the CCC.

9. The binary equivalent of 122 m of EIA tape can be loaded into the DDNC in approximately 750 ms.

MACHINING RESULTS USING DIRECT DIGITAL NUMERICAL CONTROL

An inner contour for 30 parts of the same type was machined using an Ex-Cell-O 922 turning machine with NC control. Thirty additional parts of the same type were machined using another Ex-Cell-O 922 with DDNC. Statistical results for the machining operations are reported individually in Figures 9 and 10. The 95% process capability, repeatability at a latitude, and variation between latitudes are figures of merit used to evaluate and/or compare machine performance.

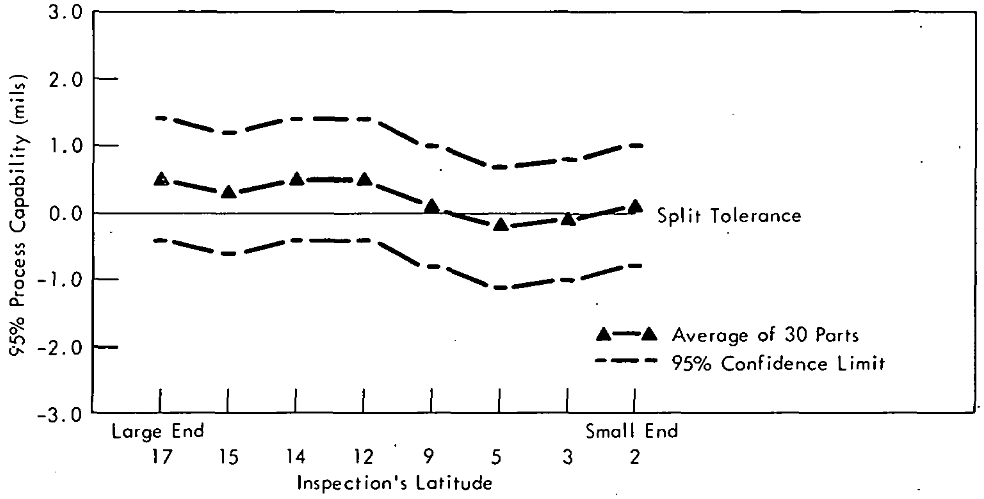

Figure 9. INNER-CONTOUR MACHINING RESULTS WITH NUMERICAL CONTROL. (95% Process Capability, ± 1.2 Mils; Repeatability at a Latitude, ± 0.9 Mil; Variation between Latitudes, 0.7 Mil)

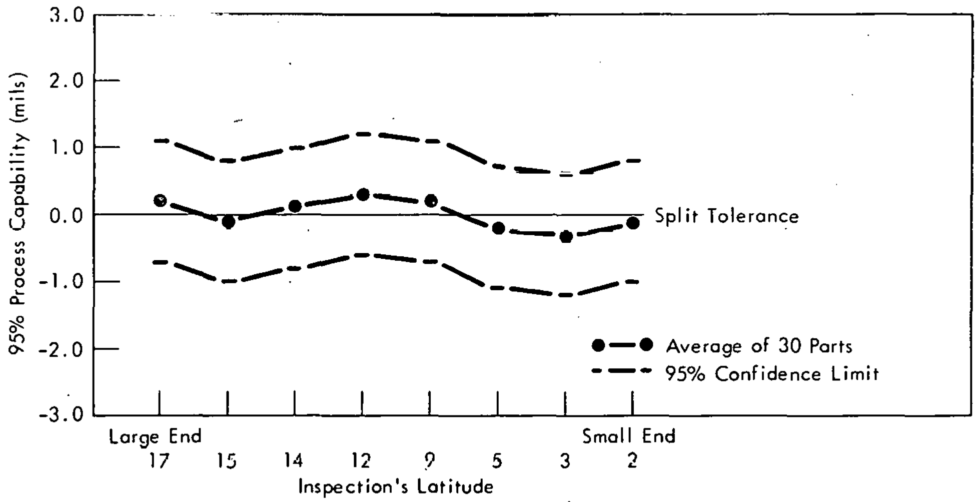

Figure 10. INNER-CONTOUR MACHINING RESULTS WITH DIRECT DIGITAL NUMERICAL CONTROL. (95% Process Capability, ± 1.2 Mils; Repeatability at a Latitude, ± 0.9 Mil; Variation between Latitudes, 0.6 Mil)

Figure 11 is a graph comparing the average of 30 parts from each machine and showing points where significant statistical differences exist. These data indicate no difference in process capability and repeatability between the two systems. However, there are some points where statistical differences exist on the part contours, as indicated in Figure 11. This graph shows the part contour average of the DDNC open-loop system to be better centered about the zero deviation or split-tolerance reference. This difference can best be explained by the fact that the DDNC open-loop system is inherently a stiffer, closer-following system. The only lag-contributing factor is the inertia of the system compared to the closed-loop NC which has a programmed following error (velocity lag) of one mil per inch per minute of feedrate in addition to the inertia lag. In fact, the slide-following error of the DDNC system (as measured by dynamic error monitor instrumentation) was one half to one third as much as a conventional closed-loop system on the same type of machine, confirming the theory that a stiffer system should follow the commanded position more closely and with less skewing than a software system with a larger following error. This belief was further confirmed by the fact that the program for a different part on a conventional NC machine had to be biased in two radial areas in order to machine the contour within tolerance, whereas unbiased data had to be used on the DDNC open-loop system.

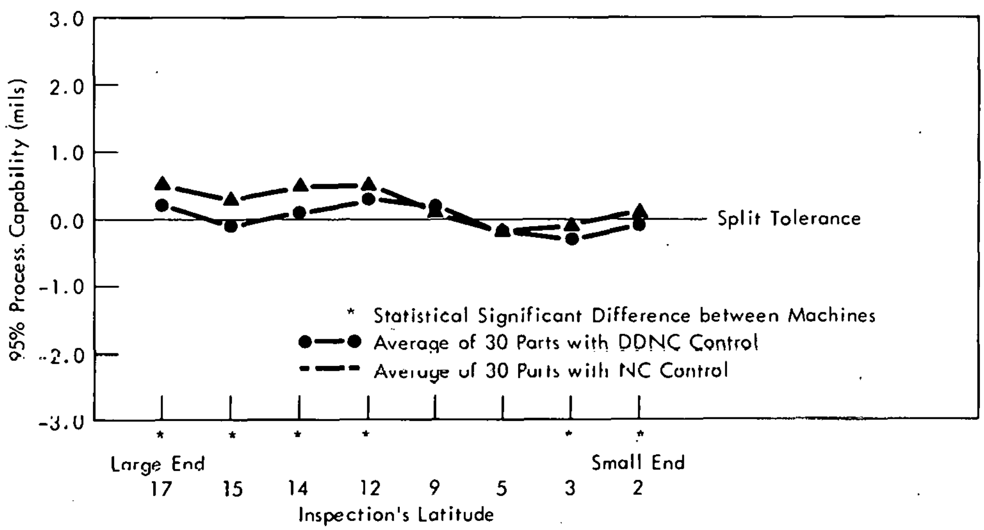

Figure 11. COMPARISON OF THIRTY PARTS MACHINED BY DIRECT DIGITAL NUMERICAL CONTROL AND BY NUMERICAL CONTROL.

CONCLUSIONS AND RECOMMENDATIONS

DDNC is a significant advancement over conventional NC and has proven to be a practical and economical method for machine-tool control. With access to the central control computer, DDNC provides a system capable of reducing the turn-around time for machining special, low-volume, custom-made parts. DDNC is also feasible for regular, high-volume machining as well as special, low-volume work. It is recommended that DDNC be considered when upgrading existing machines or purchasing new machine tools.

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(1) Williams, T. L., Burkhardt, J. H., Jr., Lay, C. M., and Stephens, A. E.; *A Two-Axis Machine Tool Control With a Dedicated Minicomputer*, Y-1865; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; February 9, 1973.

(2) Bowers, G. L.; *Machine Tool Control Via a Minicomputer*, Y-1870; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; April 18, 1973.

(3) Williams, T. L.; *Magnetic Core Memory For a Numerical Control System*, Y-1882; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; July 11, 1973.

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APPENDIX A

EIA AND BINARY FORMATTED DATA STORAGE COMPARISON

1. EIA tape has 10 characters/inch.

2. Typical data block has 20 characters/block.

3. Therefore, one block = 2 inches of EIA tape.

4. Memory capacity = 8 K of 36-bit words, for DDNC = 288×10^3 bits.

5. Binary-formatted EIA data requires on an average of two 36-bit words/block or 72 bits/block:

$$\frac{288 \times 10^3 \text{ bits}}{72 \text{ bits/block}} = 4 \times 10^3 \text{ blocks,}$$

(4000 blocks) (2 inches/block) = 8000 inches,

$$\frac{8000}{12} = 666 \text{ ft (203 m) of EIA tape.}$$

6. Storing EIA data, assuming 8 bits/EIA character, and using 20 characters/block gives:

(20 characters/block) x (8 bits/character) = 160 bits/block.

7. For memory capacity of 288×10^3 bits:

$$\frac{288 \times 10^3 \text{ bits}}{160 \text{ bits/block}} = 1.8 \times 10^3 \text{ blocks,}$$

(1800 blocks) x (2 inches/block) = 3600 inches,

$$\frac{3600}{12} = 300 \text{ ft (91 m) of EIA tape.}$$

8. Comparing Statements 5 and 7 for 8 K of 36-bit words:

Binary formatted data = 203 m of EIA tape,

EIA data storage = 91 m of EIA tape.

Data-stacking density is improved better than 2 to 1 with binary-formatted data. Table A-1 summarizes the storage comparison of binary-formatted data and EIA-coded part description data.

Table A-1

COMPARISON OF DATA STACKING DENSITY BETWEEN BINARY FORMAT AND EIA CODE

Item	EIA Code	Binary Format
Number of Bits/Data Block	20 Characters (avg) 160 Bits	2 Words (avg) 72 Bits
Number of Data Blocks to Fill 8 K x 36-Bit Memory	1800	4000
Stacking Density Ratio = X/1800	1.0	2.22

APPENDIX B

DETAILED ENGINEERING DRAWINGS

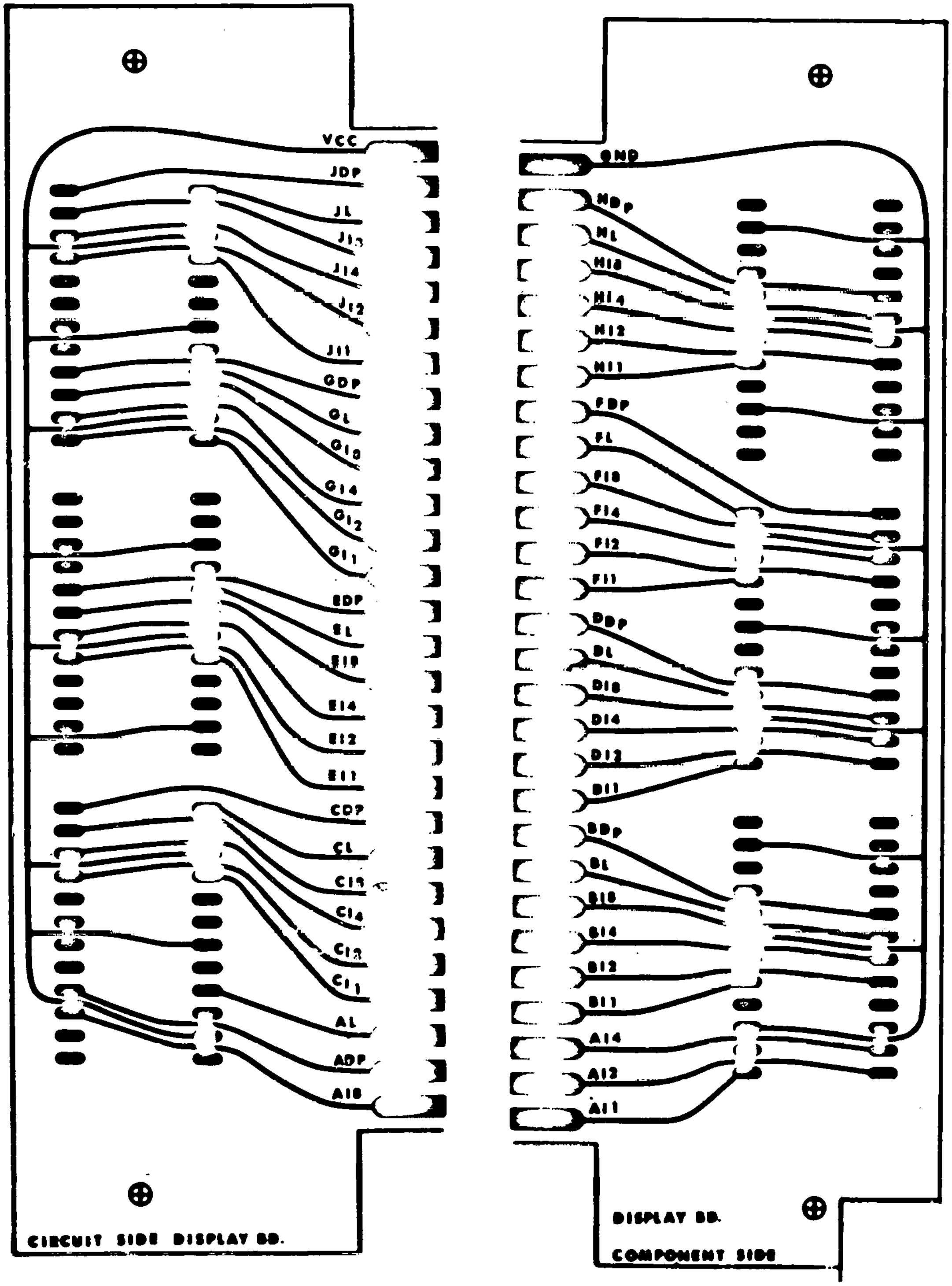


Figure B-1. DIRECT DIGITAL NUMERICAL CONTROLLER. (Display Board)

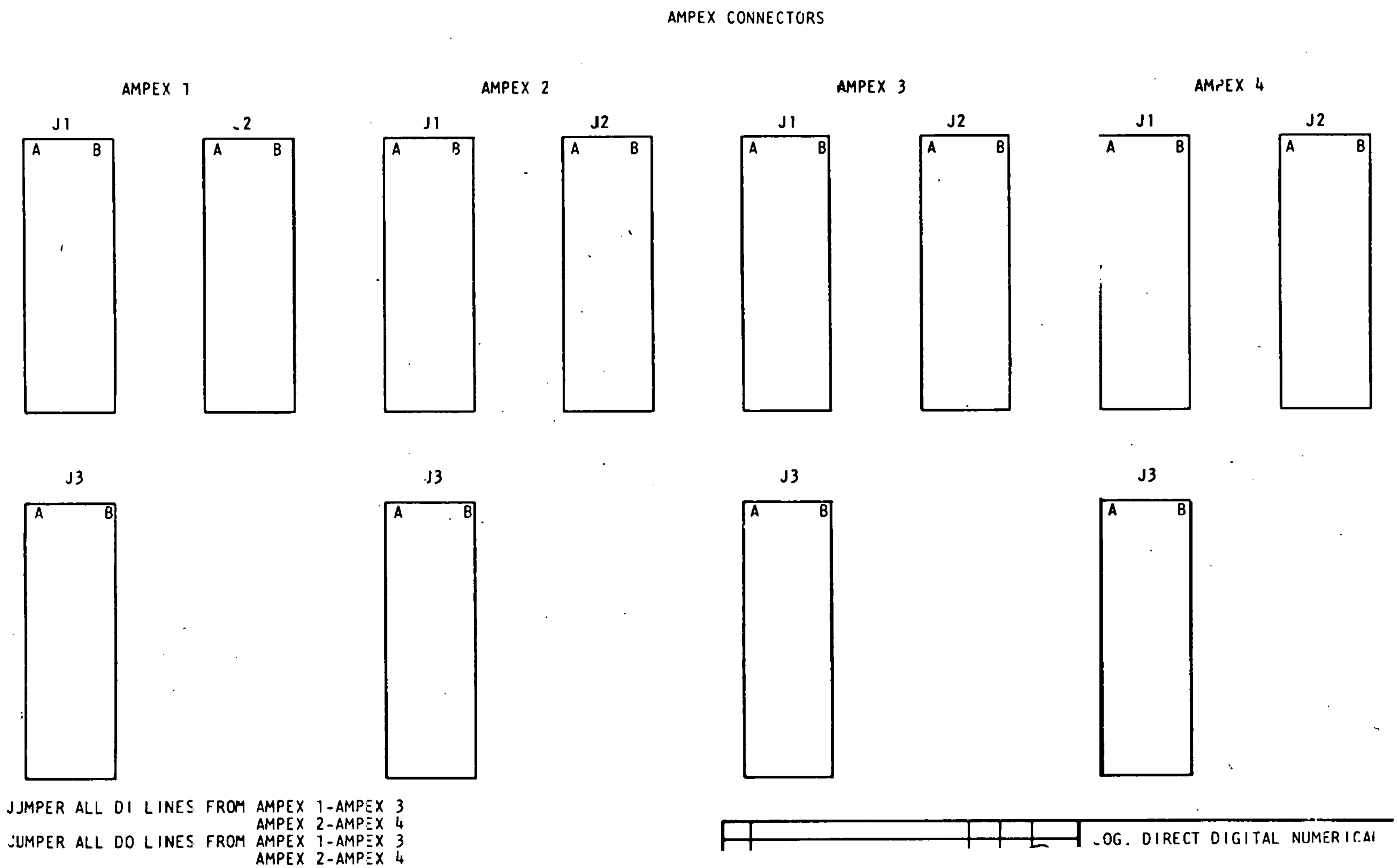


Figure B-2. DIRECT DIGITAL NUMERICAL CONTROLLER. (Ampex Connector Schedule)

AMPEX WIRING LIST

BUS LARGE WIRE (•)		
	+5 VOLTS	J2-2AB
		J1-2AB
	-15 VOLTS	J3-1AB
		J3-2AB
	GND	J2-1AB
		J1-1AB

BUS ALL PIN CONNECTIONS LISTED ON AMPEX 1, 2, 3, & 4

PINS	FROM	TO	FROM	TO	FROM	TO
-6A	A4J2-23A	A3J2-23A	A1J3-7A	A3J3-7A	A2J1-22B	A4J1-22B
-7A	A4J2-24A	A3J2-24A	A1J3-7B	A3J3-7B	A2J3-4A	A4J3-4A
-5A	A2J2-23A	A1J2-23A	A1J1-18A	A3J1-18A	A2J3-4B	A4J3-4B
-4A	A2J2-24A	A1J2-24A	A1J1-18B	A3J1-18B	A2J3-7A	A4J3-7A
-3A	A4J2-23B	A3J2-23B	A1J1-15A	A3J1-15A	A2J3-7B	A4J3-7B
-8A	A4J2-24B	A3J2-24B	A1J1-15B	A3J1-15B	A2J1-18A	A4J1-18A
-9A	A2J2-23B	A1J2-23B	A1J1-19A	A3J1-19A	A2J1-18B	A4J1-18B
-10A	A2J2-24B	A1J2-24B	A1J1-19B	A3J1-19B	A2J1-15A	A4J1-15A
-11A	A4J2-22B	A2J2-22B	A1J1-13A	A3J1-13A	A2J1-15B	A4J1-15B
-12B	A4J2-21B	A2J2-21B	A1J1-13B	A3J1-13B	A2J1-19A	A4J1-19A
-13B	A3J2-22B	A1J2-22B	A1J1-9A	A3J1-9A	A2J1-19B	A4J1-19B
-9B	A3J2-21B	A1J2-21B	A1J1-9B	A3J1-9B	A2J1-13A	A4J1-13A
-10B	A4J2-14B	A3J2-14B	A1J1-7A	A3J1-7A	A2J1-13B	A4J1-13B
-11B	A4J2-13B	A3J2-13B	A1J1-12A	A3J1-12A	A2J1-9A	A4J1-9A
-5B	A1J2-14B	A2J2-14B	A1J1-12B	A3J1-12B	A2J1-9B	A4J1-9B
-4B	A1J2-13B	A2J2-13B	A1J1-3A	A3J1-3A	A2J1-7A	A4J1-7A
-3B	A1J3-16A	A3J3-16A	A1J1-3B	A3J1-3B	A2J1-7B	A4J1-7B
-6B	A1J3-16B	A3J3-16B	A1J1-6A	A3J1-6A	A2J1-12A	A4J1-12A
-7B	A1J3-11A	A3J3-11A	A1J1-6B	A3J1-6B	A2J1-12B	A4J1-12B
-8B	A1J3-11B	A3J3-11B	A2J3-16A	A4J3-16A	A2J1-3A	A4J1-3A
-15B	A1J3-14A	A3J3-14A	A2J3-16B	A4J3-16B	A2J1-3B	A4J1-3B
-16B	A1J3-14B	A3J3-14B	A2J3-11A	A4J3-11A	A2J1-6A	A4J1-6A
-18A	A1J1-24A	A3J1-24A	A2J3-11B	A4J3-11B	A2J1-6B	A4J1-6B
-17A	A1J1-24B	A3J1-24B	A2J3-14A	A4J3-14A	A2J3-15A	A4J3-15A
-12A	A1J3-9A	A3J3-9A	A2J3-14B	A4J3-14B	A2J3-15B	A4J3-15B
J2-13A	A1J3-9B	A3J3-9B	A2J1-24A	A4J1-24A	A2J3-12A	A4J3-12A
-20A	A1J3-5A	A3J3-5A	A2J1-24B	A4J1-24B	A2J3-12B	A4J3-12B
-21A	A1J3-5B	A3J3-5B	A2J3-9A	A4J3-9A	A2J3-13A	A4J3-13A
-17B	A1J1-22A	A3J1-22A	A2J3-9B	A4J3-9B	A2J3-13B	A4J3-13B
-17A	A1J1-22B	A3J1-22B	A2J3-5A	A4J3-5A	A2J1-23A	A4J1-23A
-18B	A1J3-4A	A3J3-4A	A2J3-5B	A4J3-5B	A2J1-23B	A4J1-23B
-19B	A1J3-4B	A3J3-4B	A2J1-22A	A4J1-22A	A2J3-10A	A4J3-10A
			A1J1-7B	A3J1-7B		

Figure B-3. DIRECT DIGITAL NUMERICAL CONTROLLER. (Wiring List)

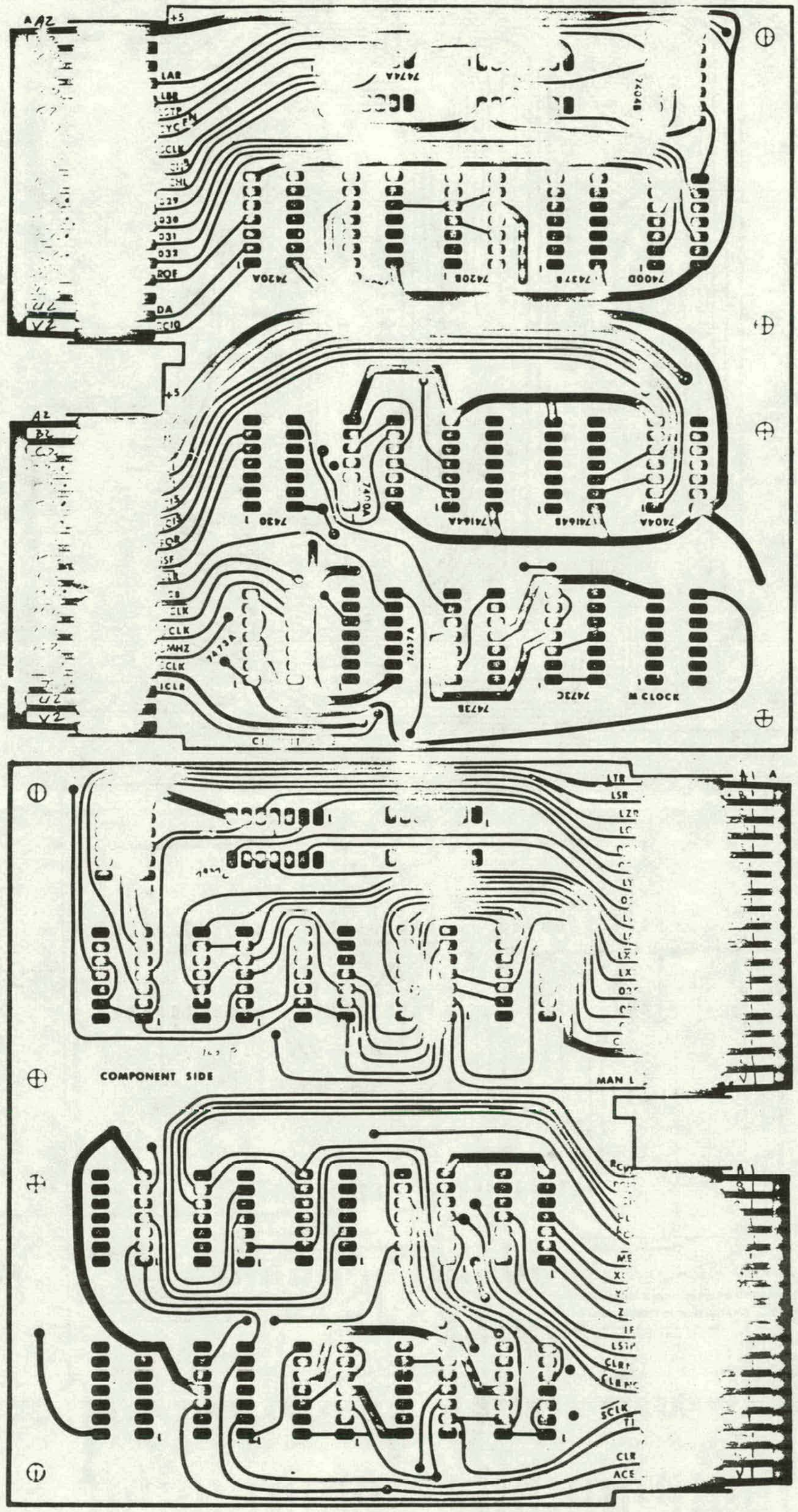


Figure B-4. DIRECT DIGITAL NUMERICAL CONTROLLER. (Readout and Load Board)

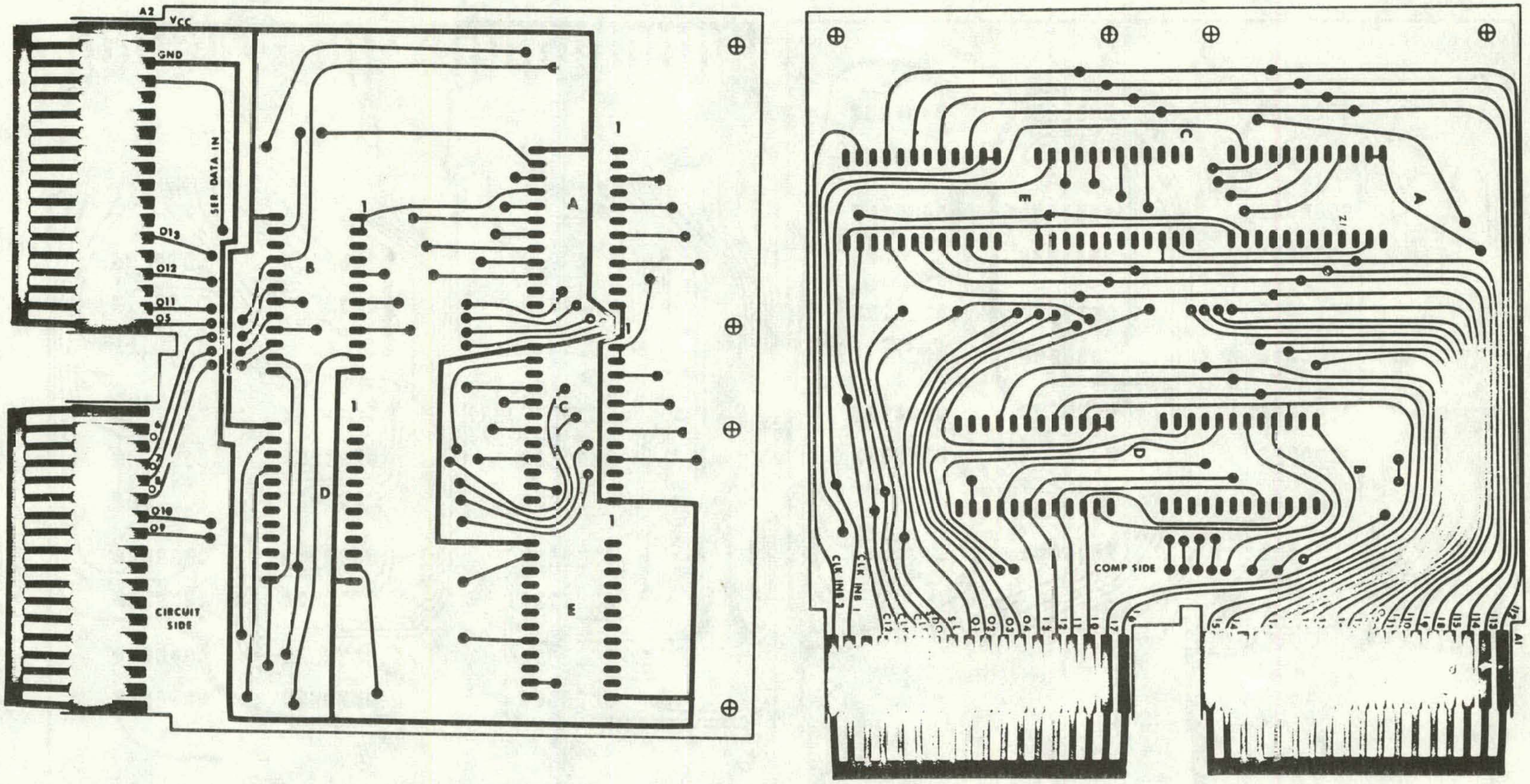


Figure B-5. DIRECT DIGITAL NUMERICAL CONTROLLER. (CCC Shift Register Board)

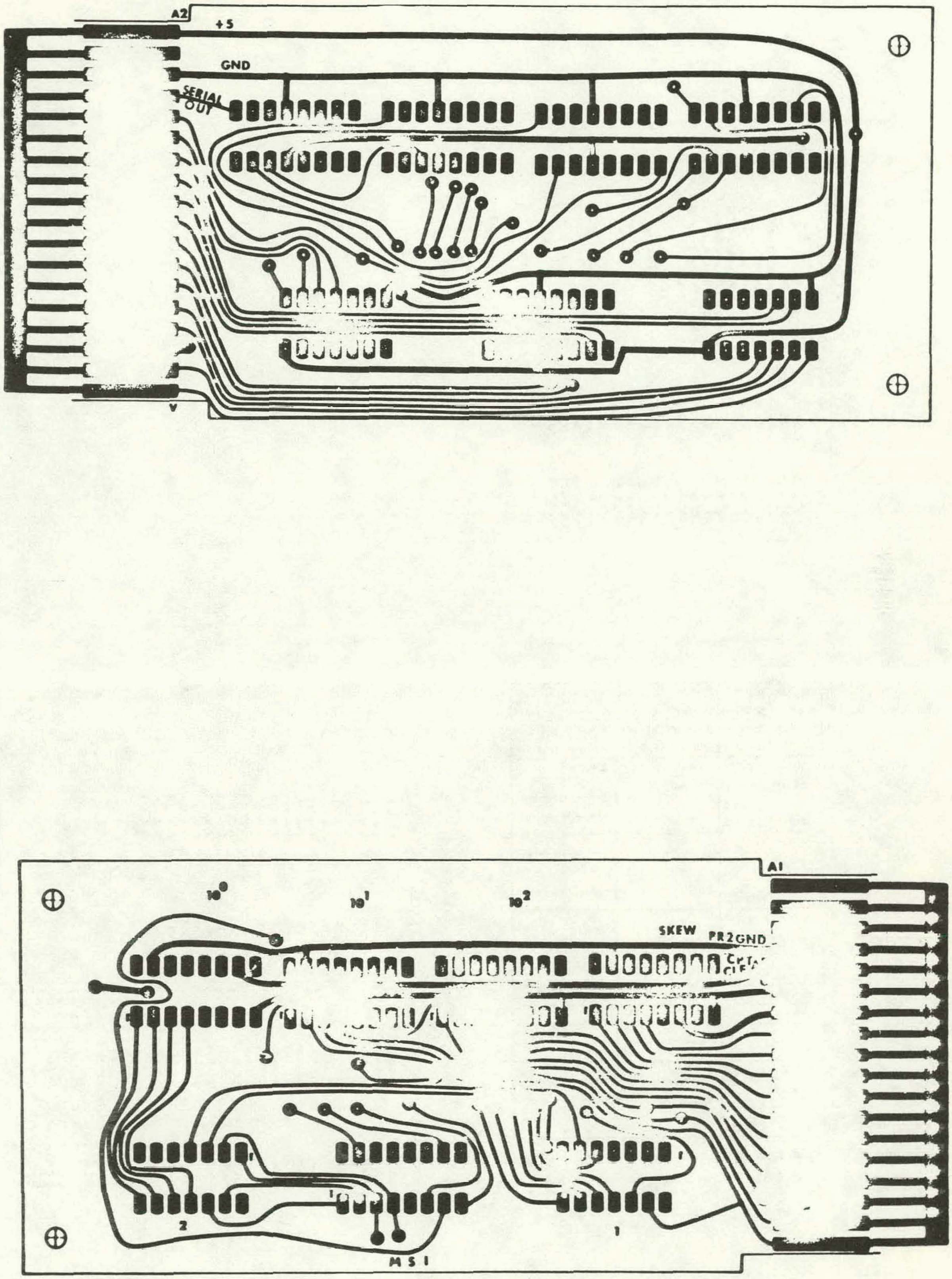
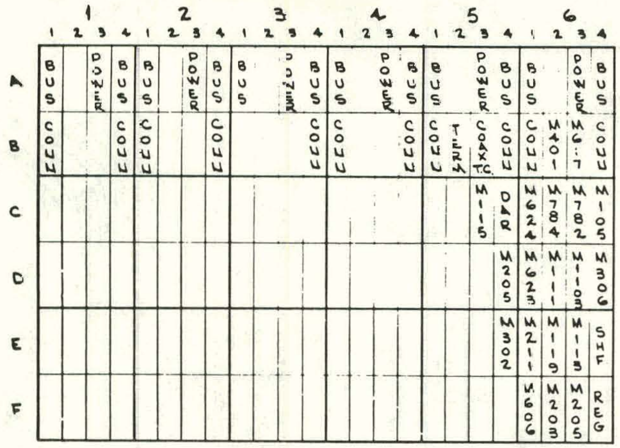


Figure B-6. DIRECT DIGITAL NUMERICAL CONTROLLER. (Shift Register P/C Layout)

SYSTEM UNIT BLOCK



20 BIT SHIFT REGISTER
(REMOTE STA. HARDWARE)

10^2 8 —	S1
10^2 4	R1
10^2 2	P1
10^2 1	N1
10^1 8	E2
10^1 4	V1
10^1 2	U1
10^1 1	T2
10^0 8	V2
10^0 4	U2
10^0 2	S2
10^0 1	R2
MSI 8	L2
MSI 4	M2
MSI 2	P2
MSI 1	N2
PARITY	M1
SKEW 1	L1
SKEW 2	K1
SKEW 3	J1

LOAD	H1
SERIAL OUTPUT	D2
CLOCK	F1
CLEAR	E1
CONTROL ADD IN	F2
CONTROL EVEN IN	H2
CONTROL ADD OUT	K2
CONTROL EVEN OUT	J2
PR2	D1

40 BIT SHIFT REGISTER
(CCC HARDWARE)

PARALLEL DATA IN		PARALLEL DATA OUT	
E4D1	D15H	20	E4K1
E4C1	D14H	19	E4L1
E4B1	D13H	18	E4M1
E4A1	D12H	17	E4N1
E4J1	D11H	16	E4P1
E4H1	D10H	15	E4R1
E4F1	D09H	14	E4S1
E4E1	D0EH	13	E4P2
F4B1	D07H	12	E4S2
F4A1	D06H	11	E4U2
F4V1	D05H	10	E4H2
F4U1	D04H	9	E4J2
F4F1	D03H	8	E4F2
F4E1	D02H	7	E4E2
F4D1	D01H	6	E4D2
F4C1	D0CH	5	E4V2
		4	F4H1
		3	F4J1
		2	F4K1
		1	F4L1

SHIFT/LOAD (S/L) – F4M1
CLOCK (CLK) – F4R1
SERIAL DATA OUT (SDO) – F4N1
CLK INB 1 (CI1) – F4U1
CLK INB 2 (CI2) – F4S1
CLK INB 3 (CI3) – F4V1
CLEAR (CLR) – F4P1
SERIAL DATA IN – E4D2

Figure B-7. DIRECT DIGITAL NUMERICAL CONTROLLER. (Shift Register Data)

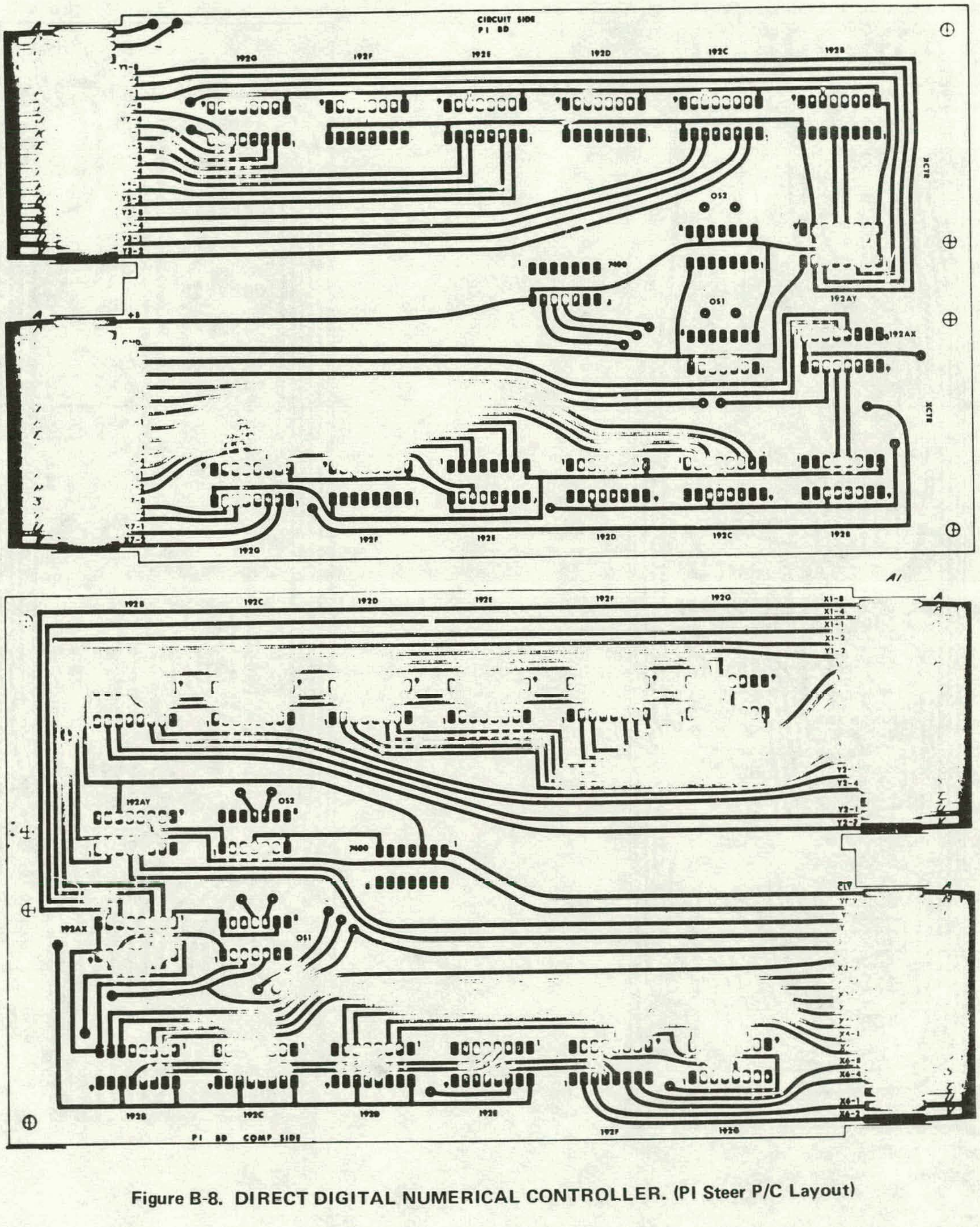


Figure B-8. DIRECT DIGITAL NUMERICAL CONTROLLER. (PI Steer P/C Layout)

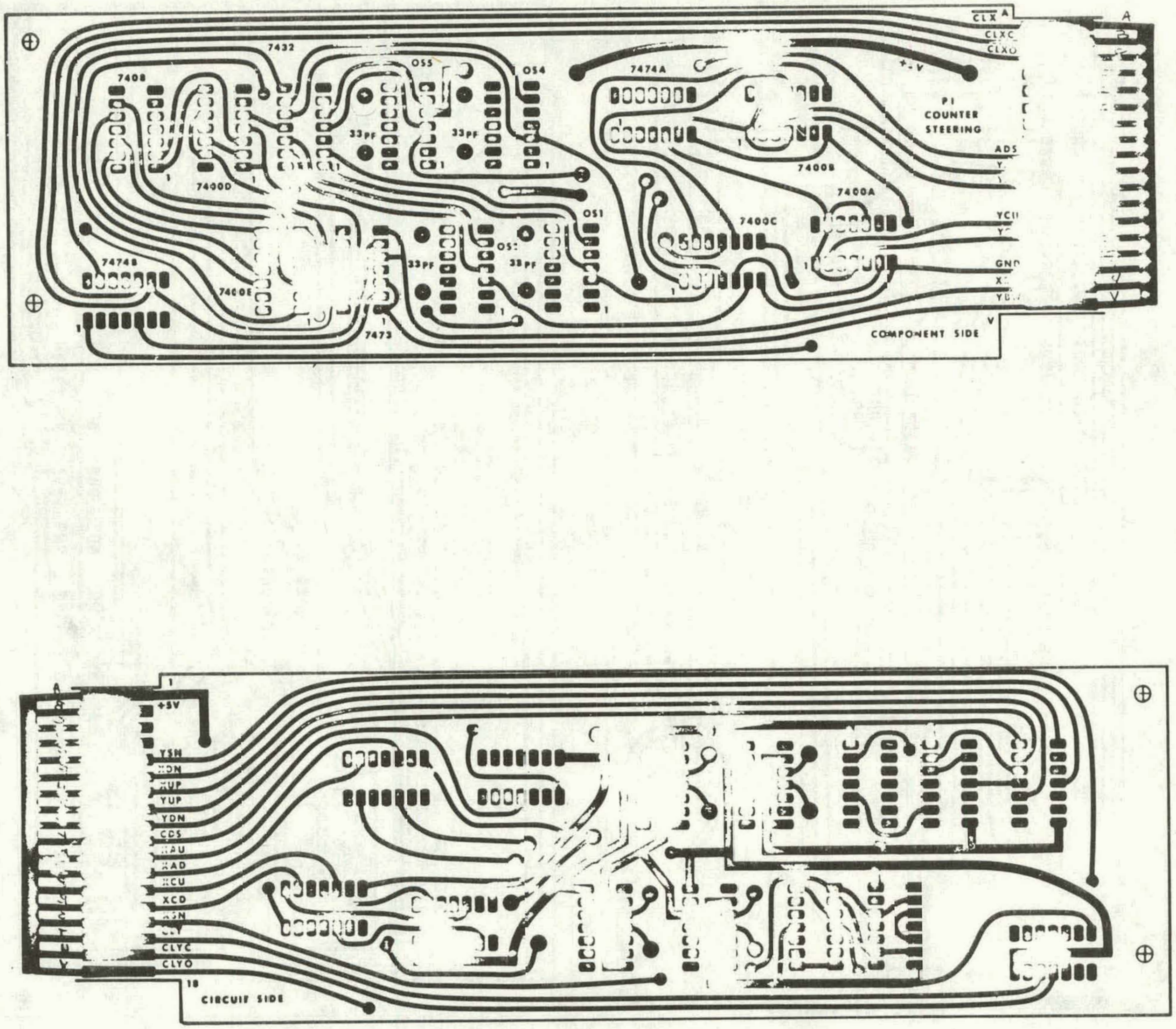


Figure B-9. DIRECT DIGITAL NUMERICAL CONTROLLER. (PI Control Steer P/C Layout)

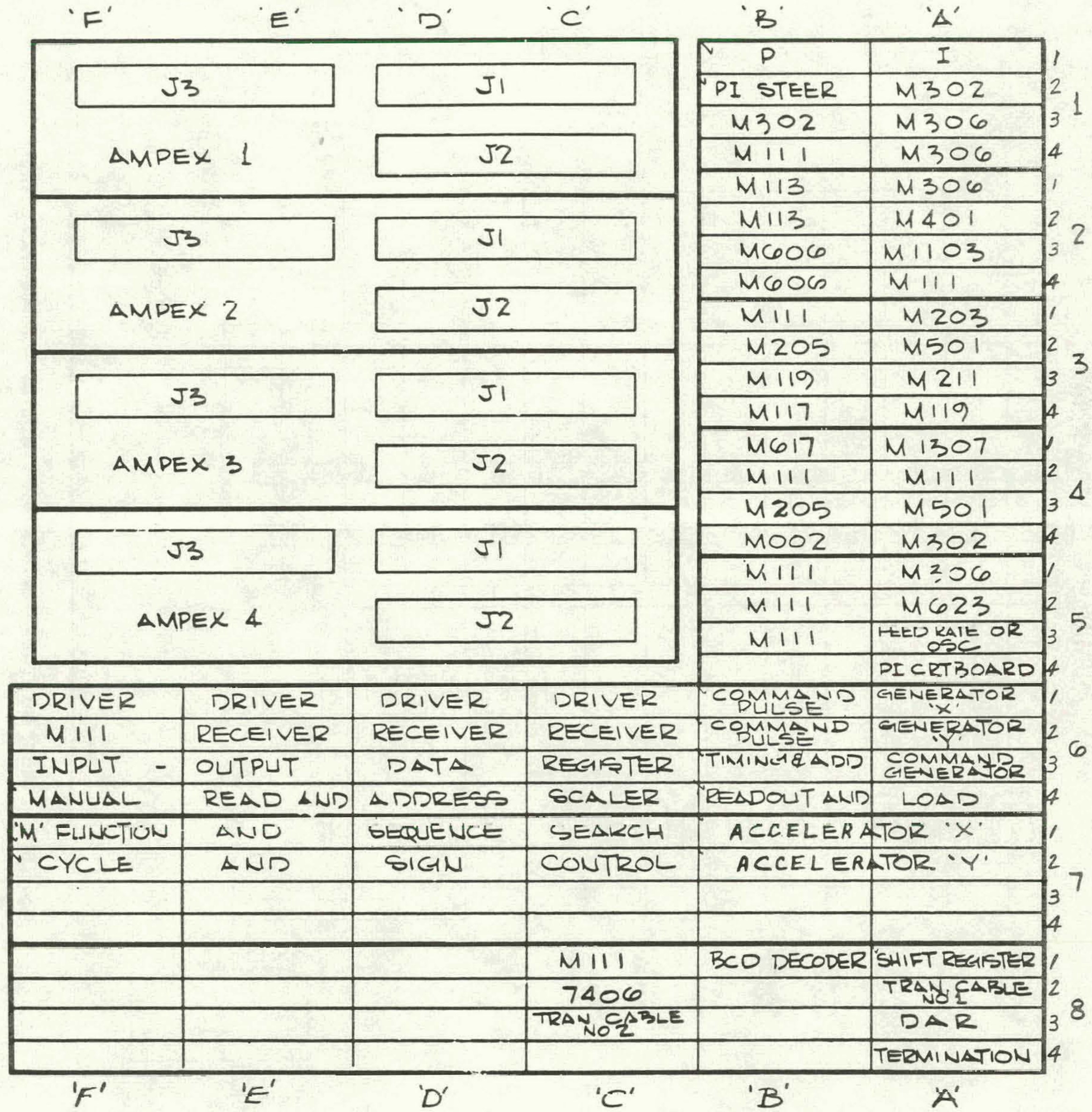
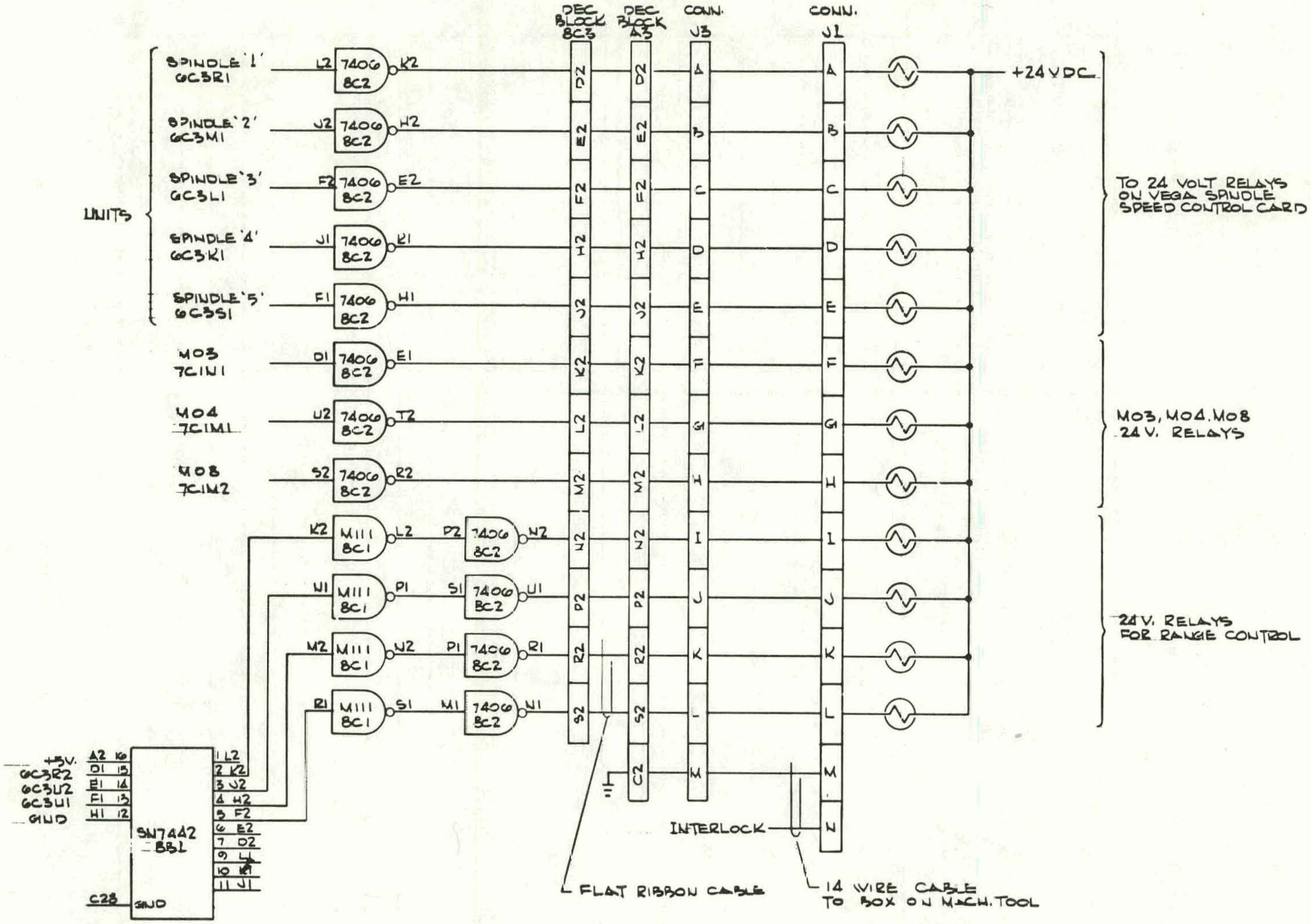
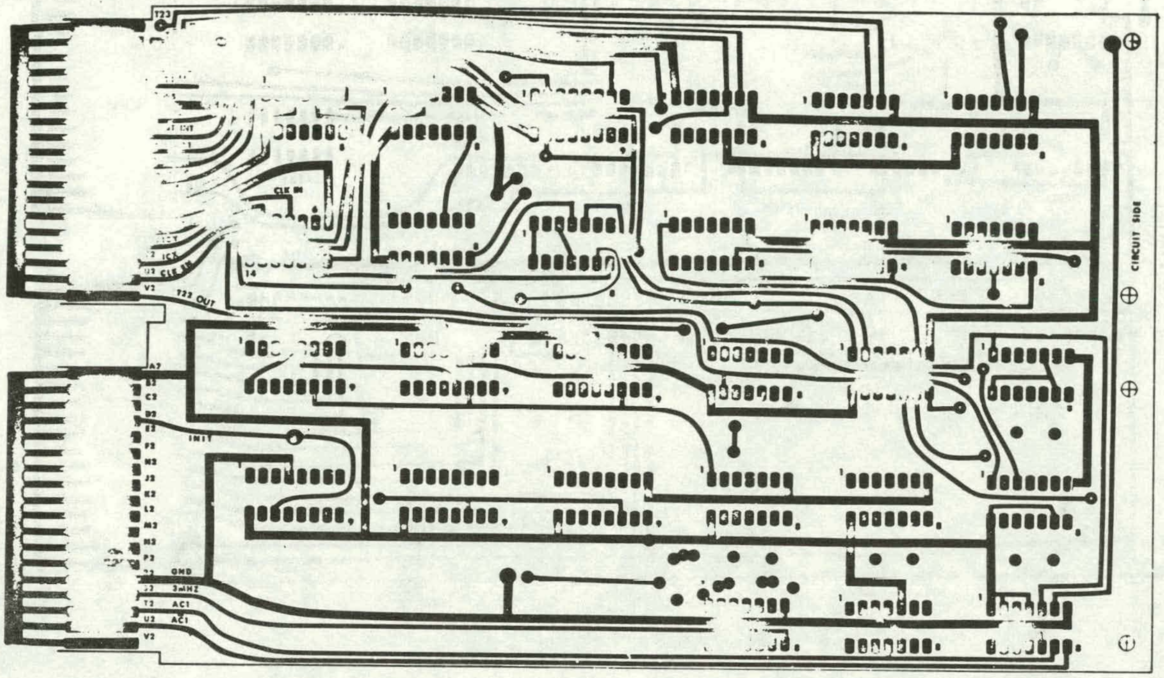


Figure B-10. DIRECT DIGITAL NUMERICAL CONTROLLER. (Module Layout)



SPINDLE SPEED, M03, M04, M08 CONTROL

Figure B-11. DIRECT DIGITAL NUMERICAL CONTROLLER. (Spindle Speed Control Logic)



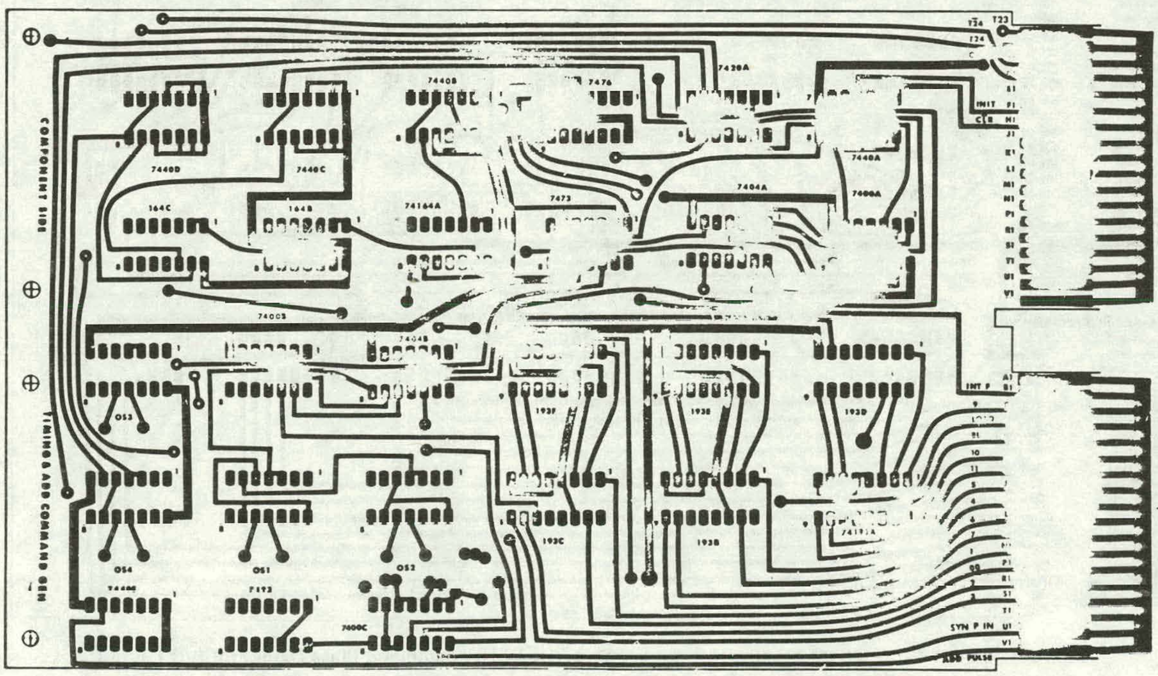
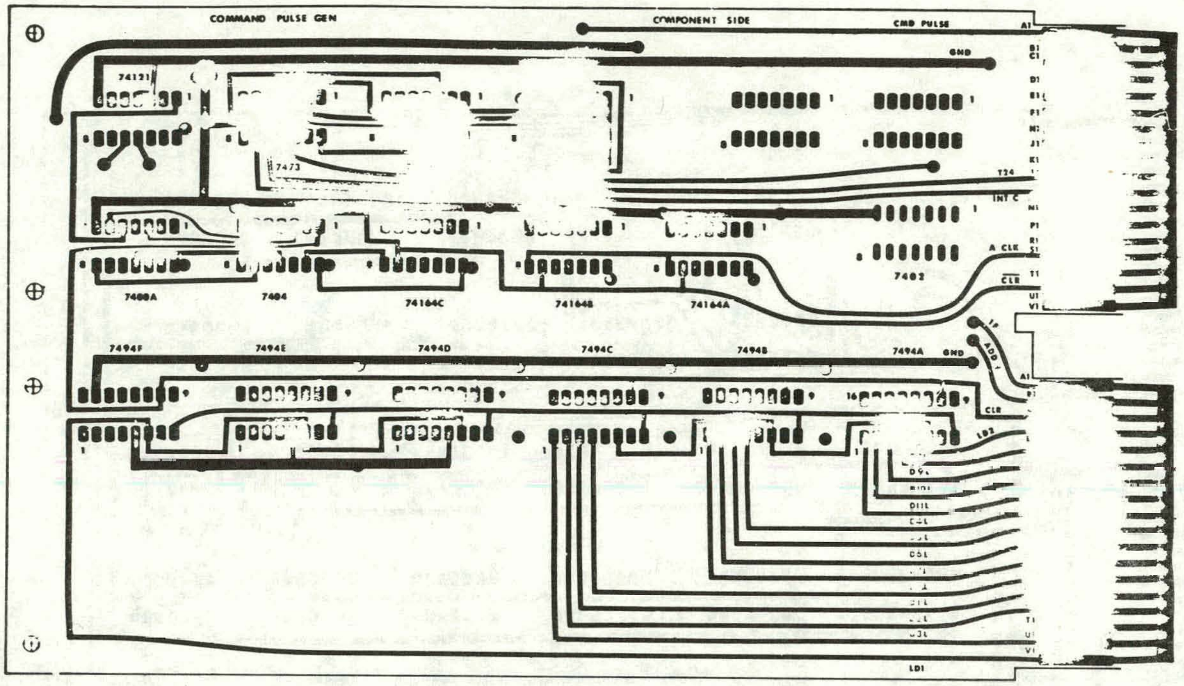


Figure B-12. DIRECT DIGITAL NUMERICAL CONTROLLER. (Time and Add Command P/C Layout)



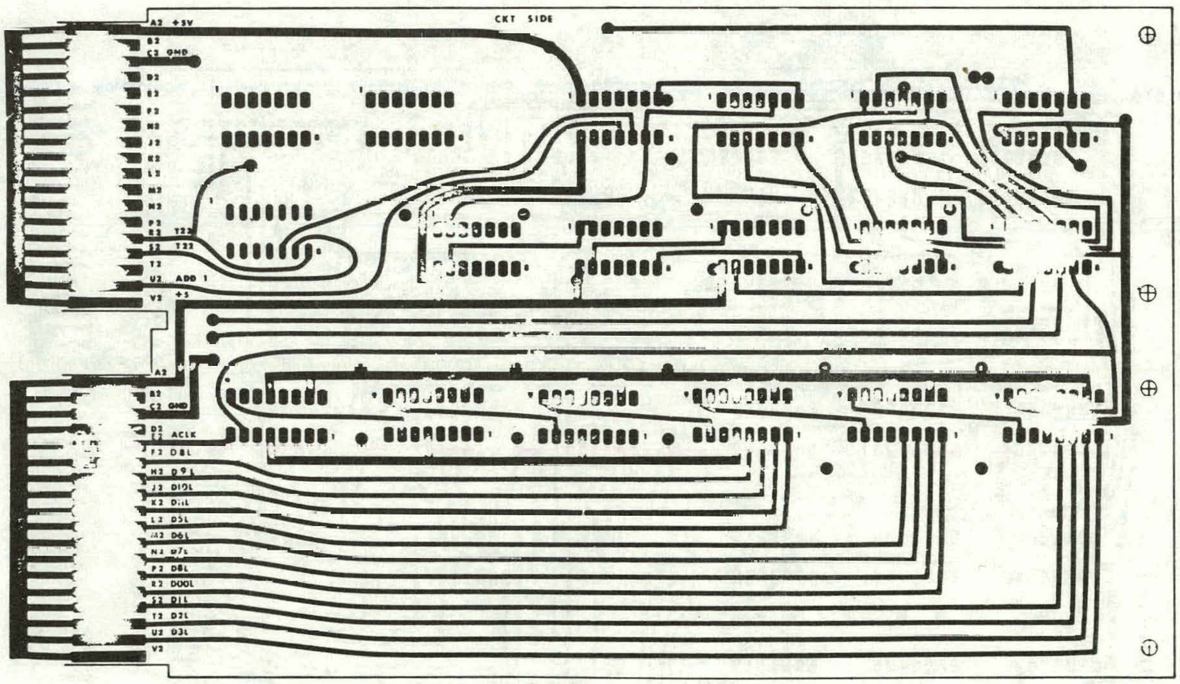


Figure B-13. DIRECT DIGITAL NUMERICAL CONTROLLER. (Command Pulse Generator P/C Layout)

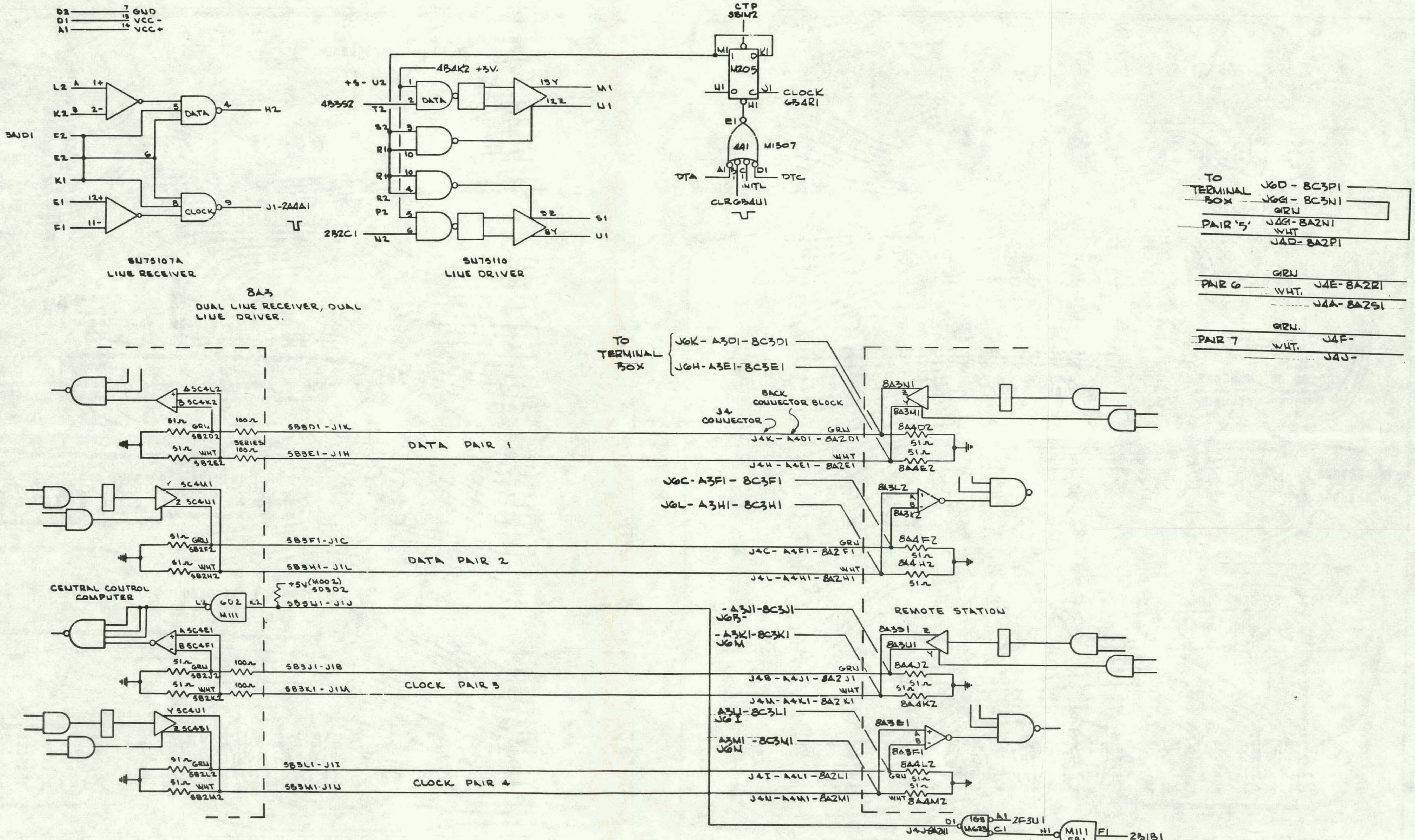


Figure B-14. DIRECT DIGITAL NUMERICAL CONTROLLER. (Remote Station Logic)

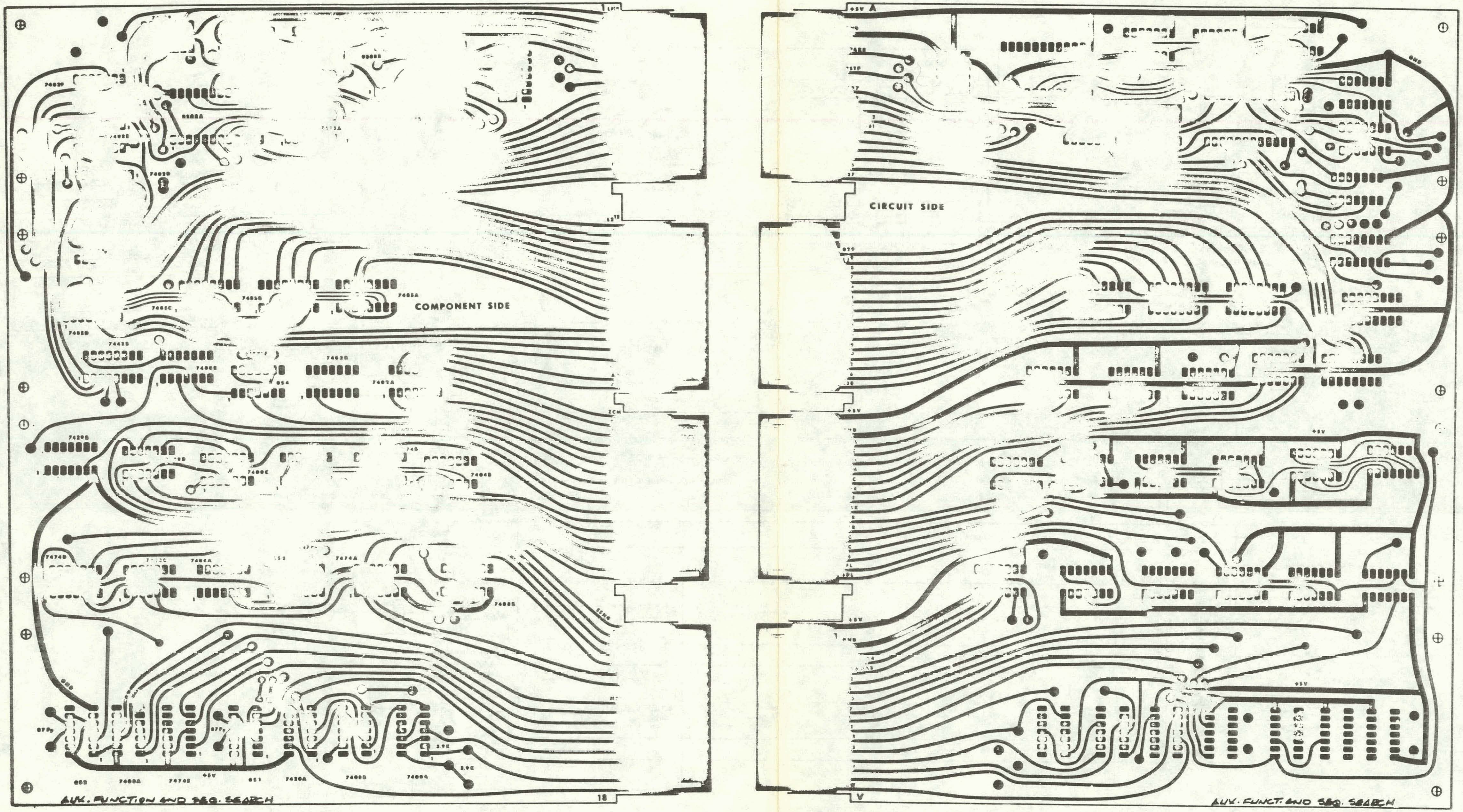


Figure B-15. DIRECT DIGITAL NUMERICAL CONTROLLER. (Auxiliary Function-Sequence Search P/C Layout)

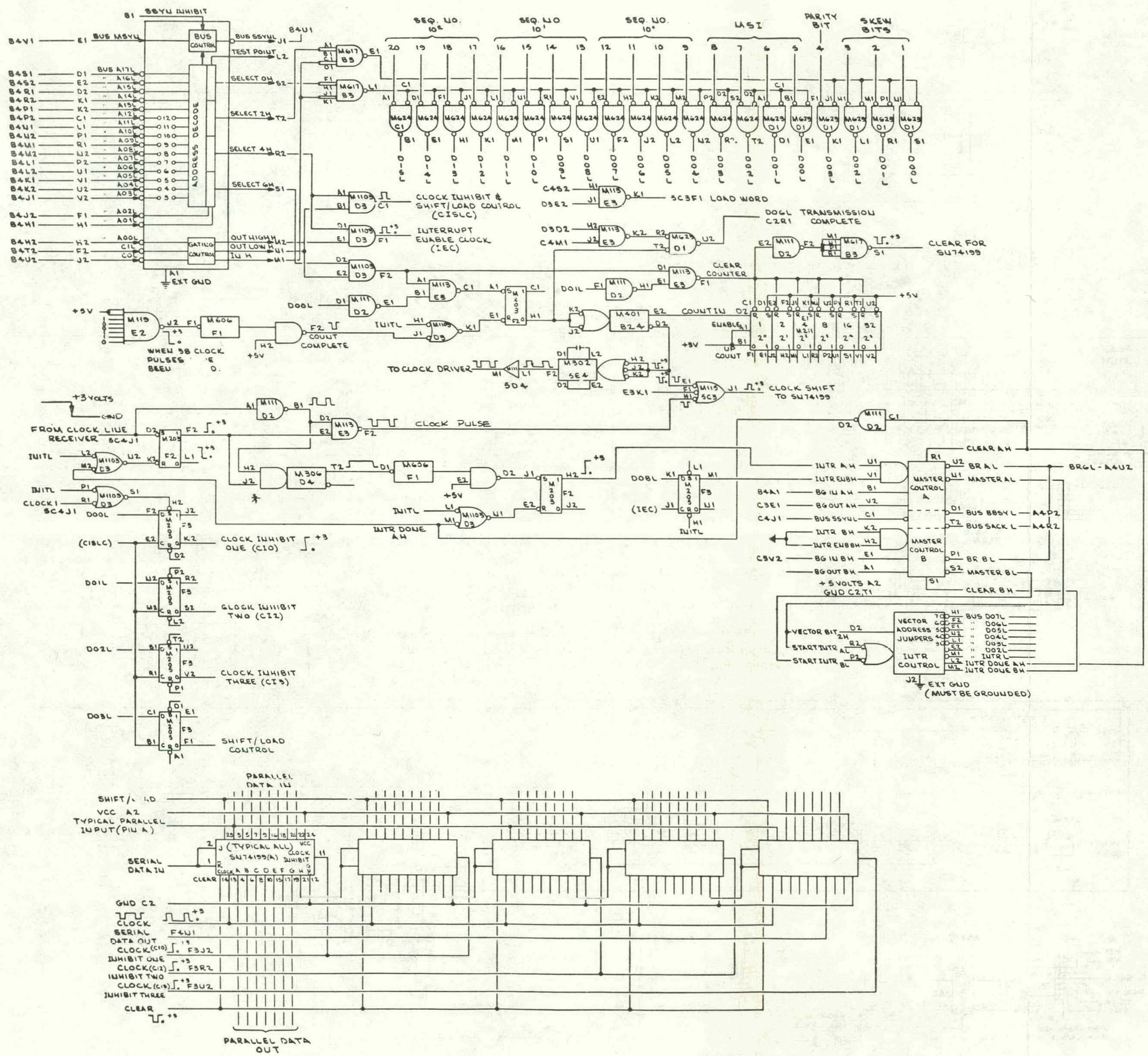


Figure B-16. DIRECT DIGITAL NUMERICAL CONTROLLER. (CCC Transmission Logic)

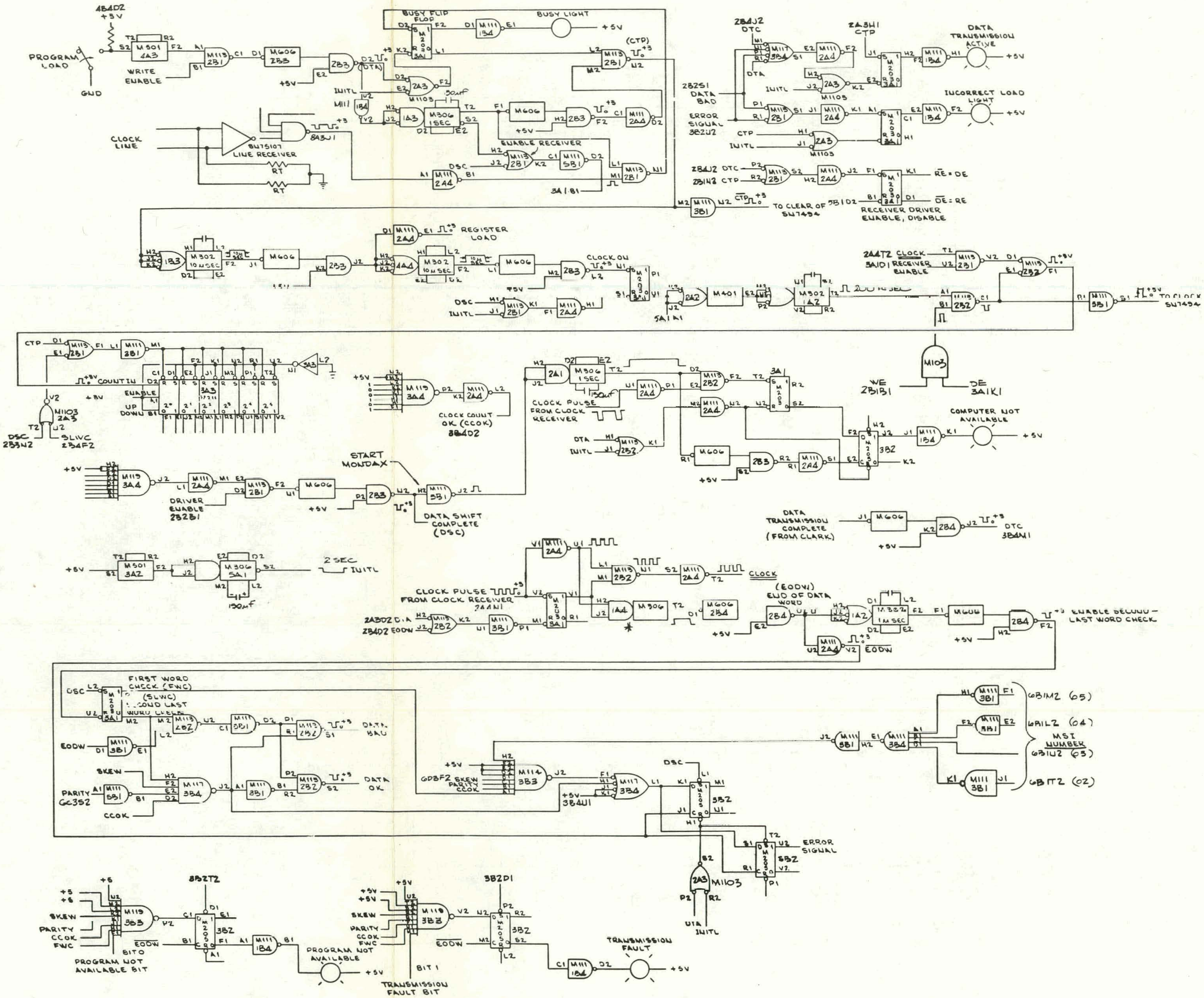


Figure B-17. DIRECT DIGITAL NUMERICAL CONTROLLER. (Remote Station Hardware)

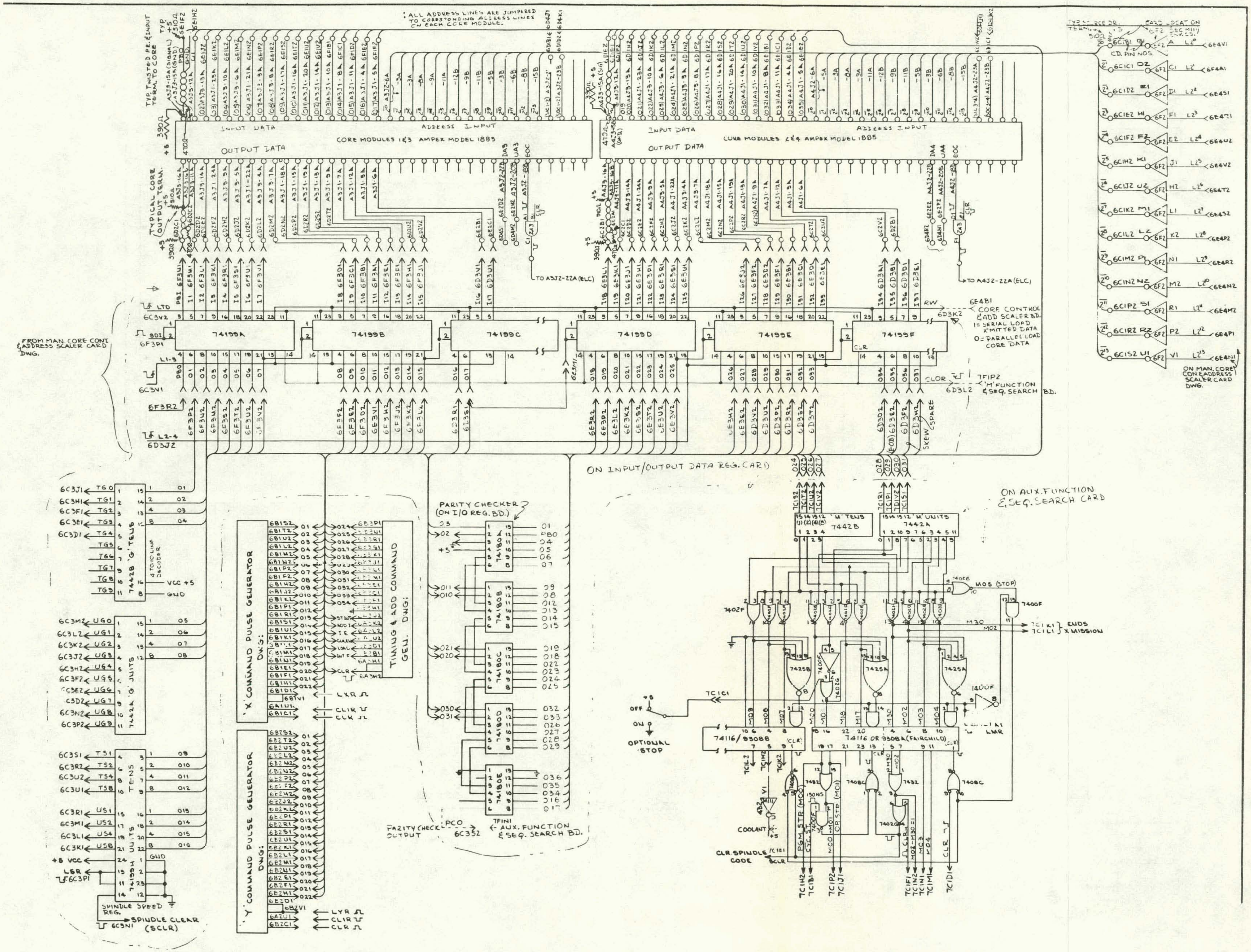


Figure B-18. DIRECT DIGITAL NUMERICAL CONTROLLER. (I/O Register-Auxiliary Function Logic)

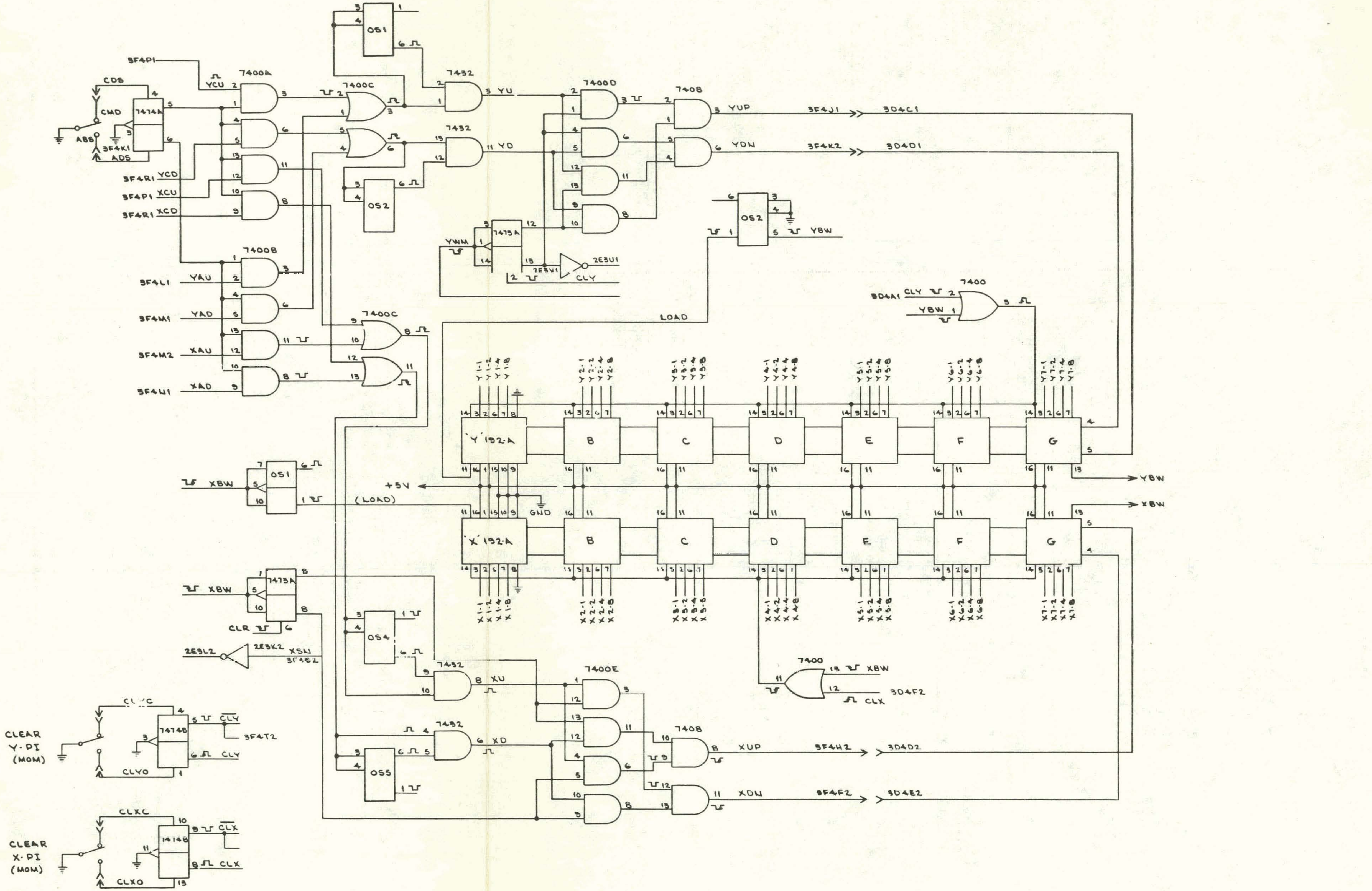


Figure B-19. DIRECT DIGITAL NUMERICAL CONTROLLER. (PI Counter Logic)

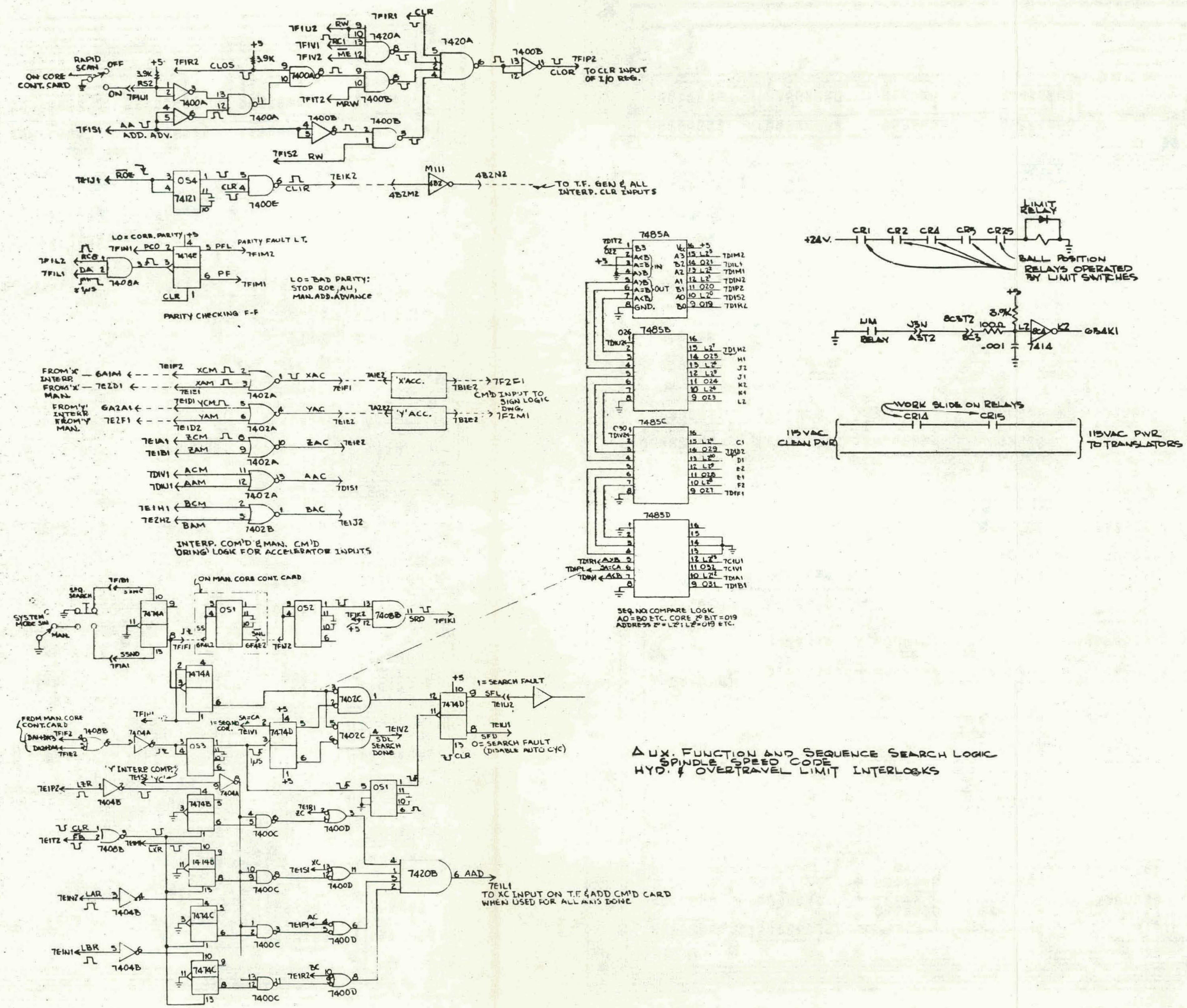


Figure B-20. DIRECT DIGITAL NUMERICAL CONTROLLER. (Auxiliary Logic-Spindle Speed Logic)

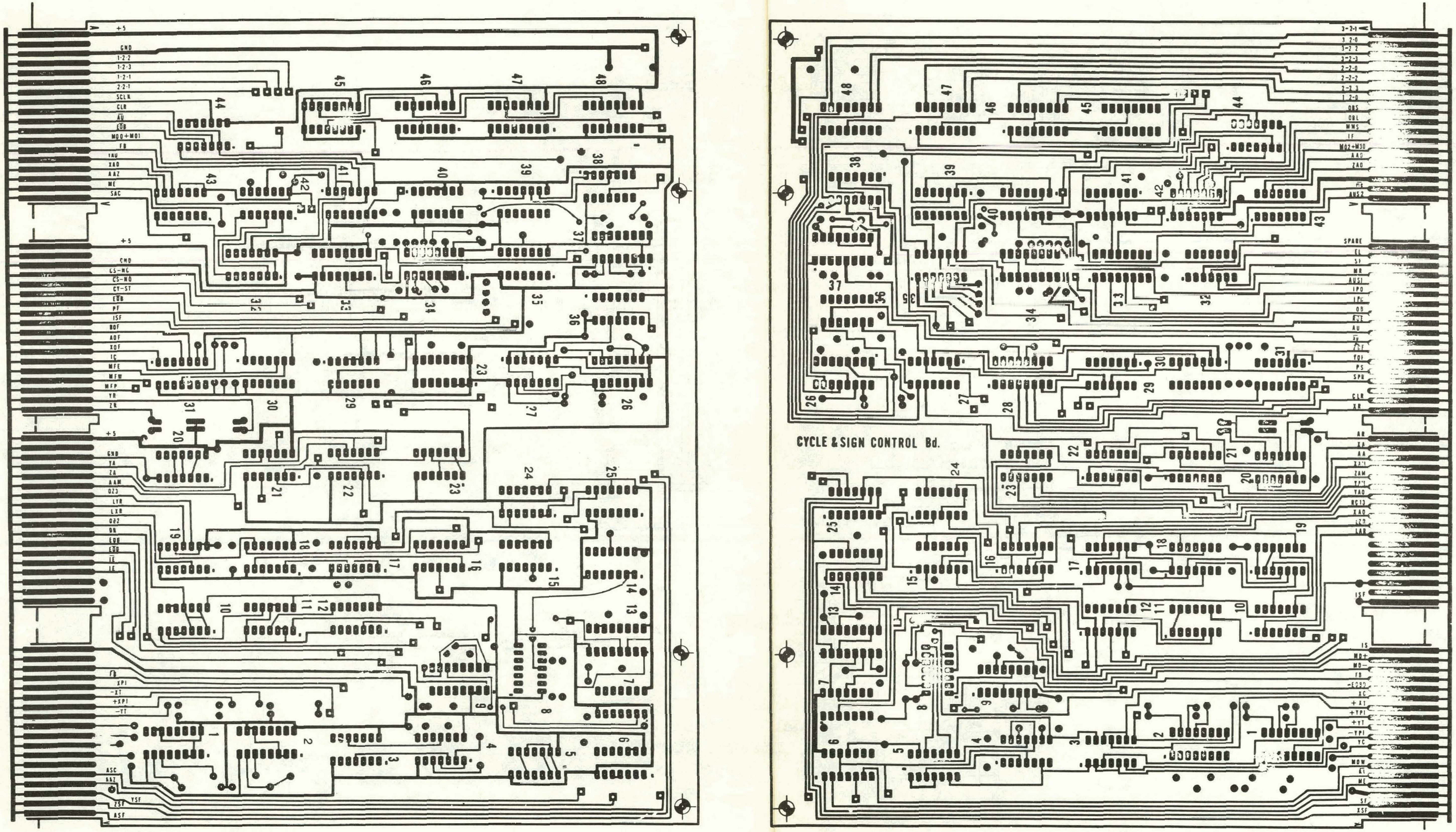


Figure B-21. DIRECT DIGITAL NUMERICAL CONTROLLER. (Cycle-Sign Control P/C Layout)

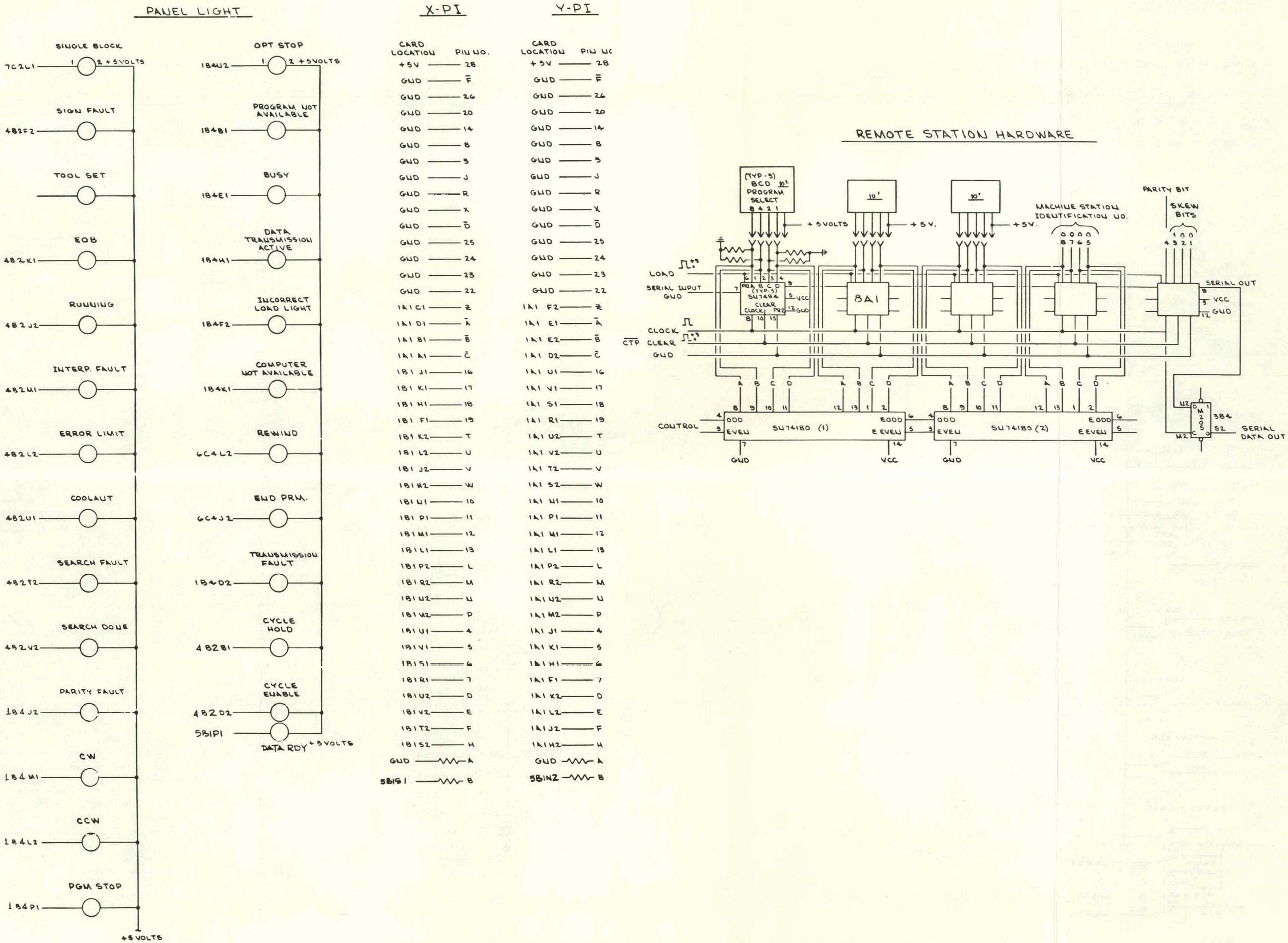


Figure B-22. DIRECT DIGITAL NUMERICAL CONTROLLER. (Miscellaneous Logic Diagrams)

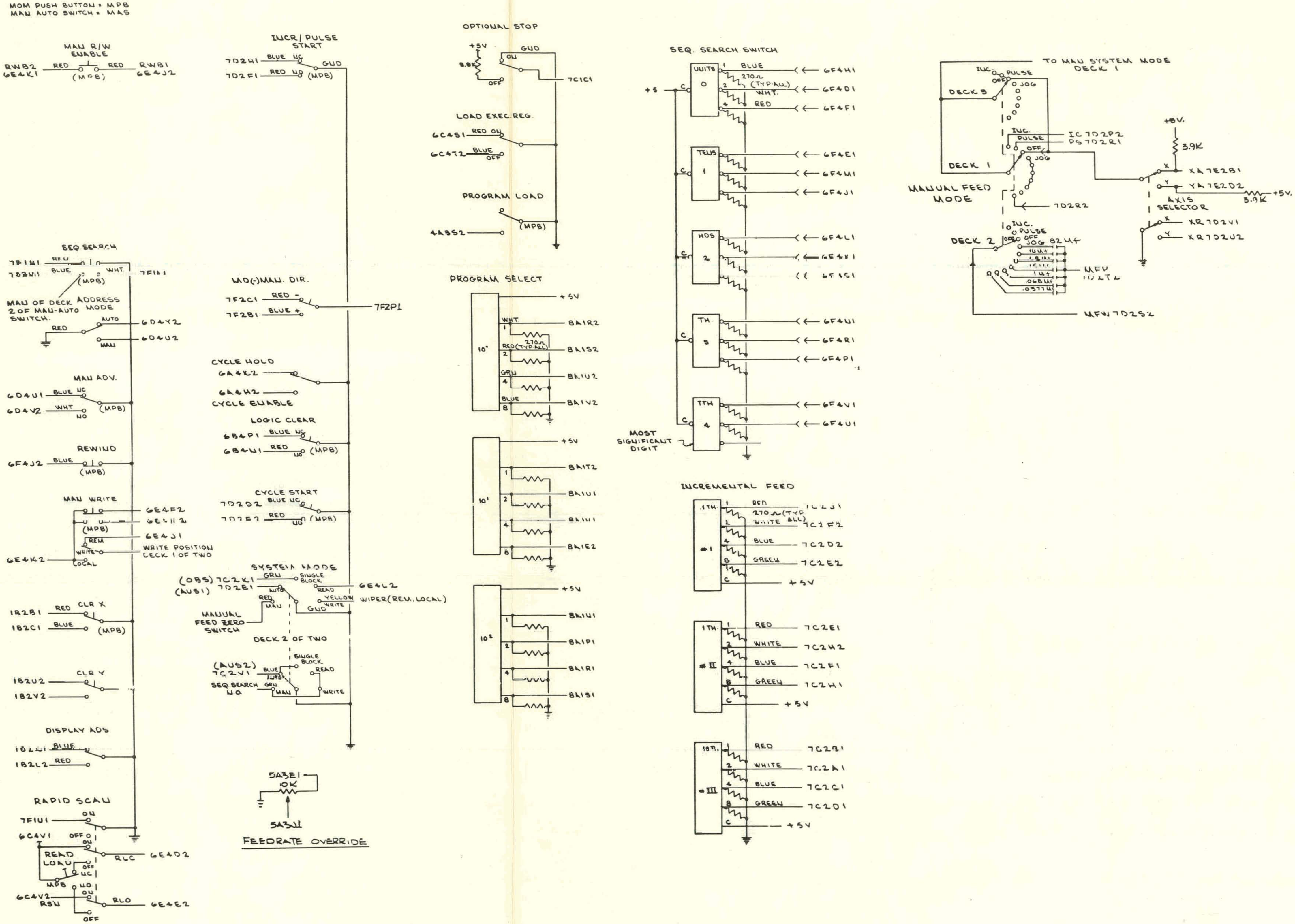


Figure B-23. DIRECT DIGITAL NUMERICAL CONTROLLER. (Miscellaneous Logic Circuits)

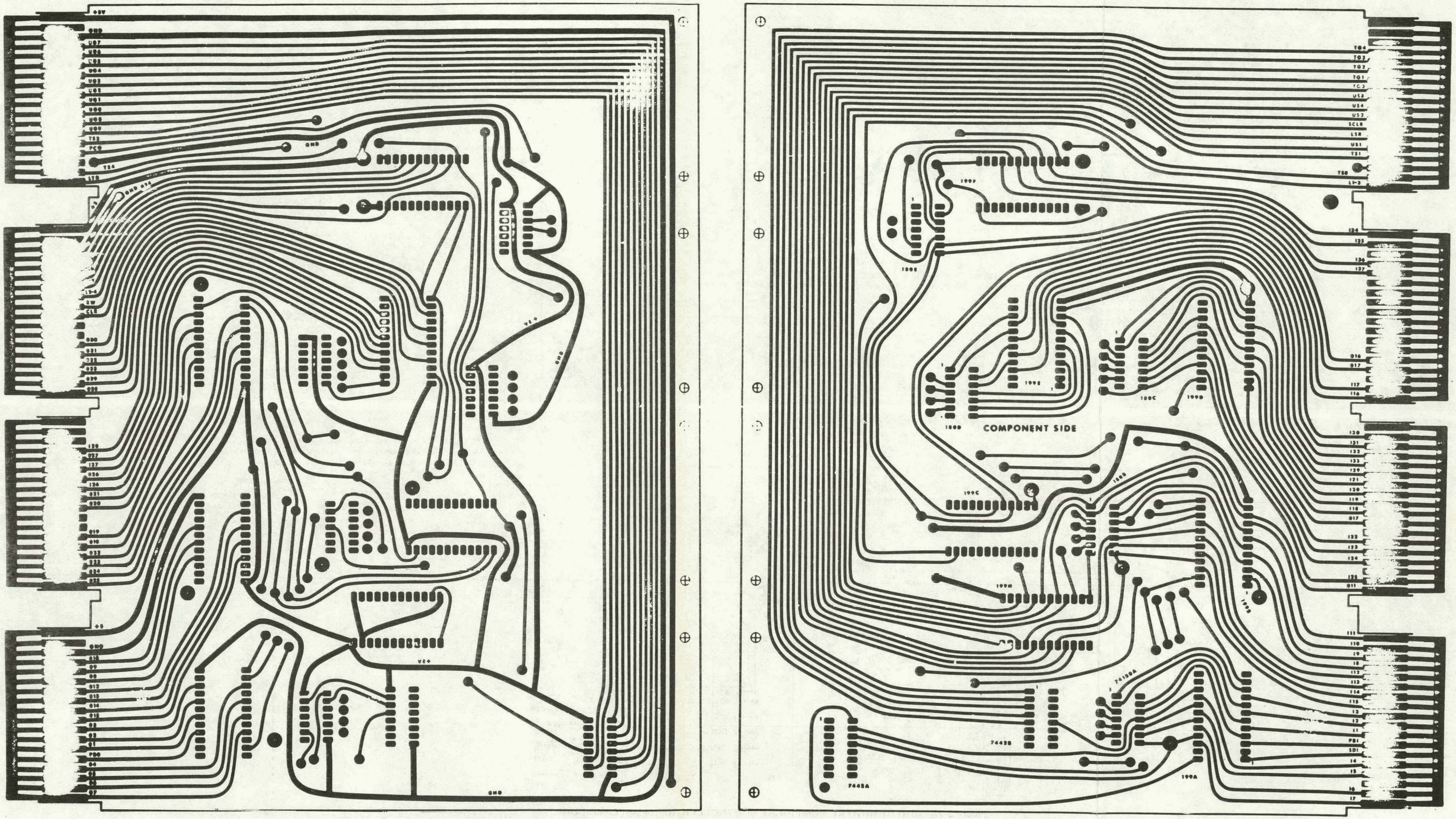


Figure B-24. DIRECT DIGITAL NUMERICAL CONTROLLER.(Input-Output Data Register Board)

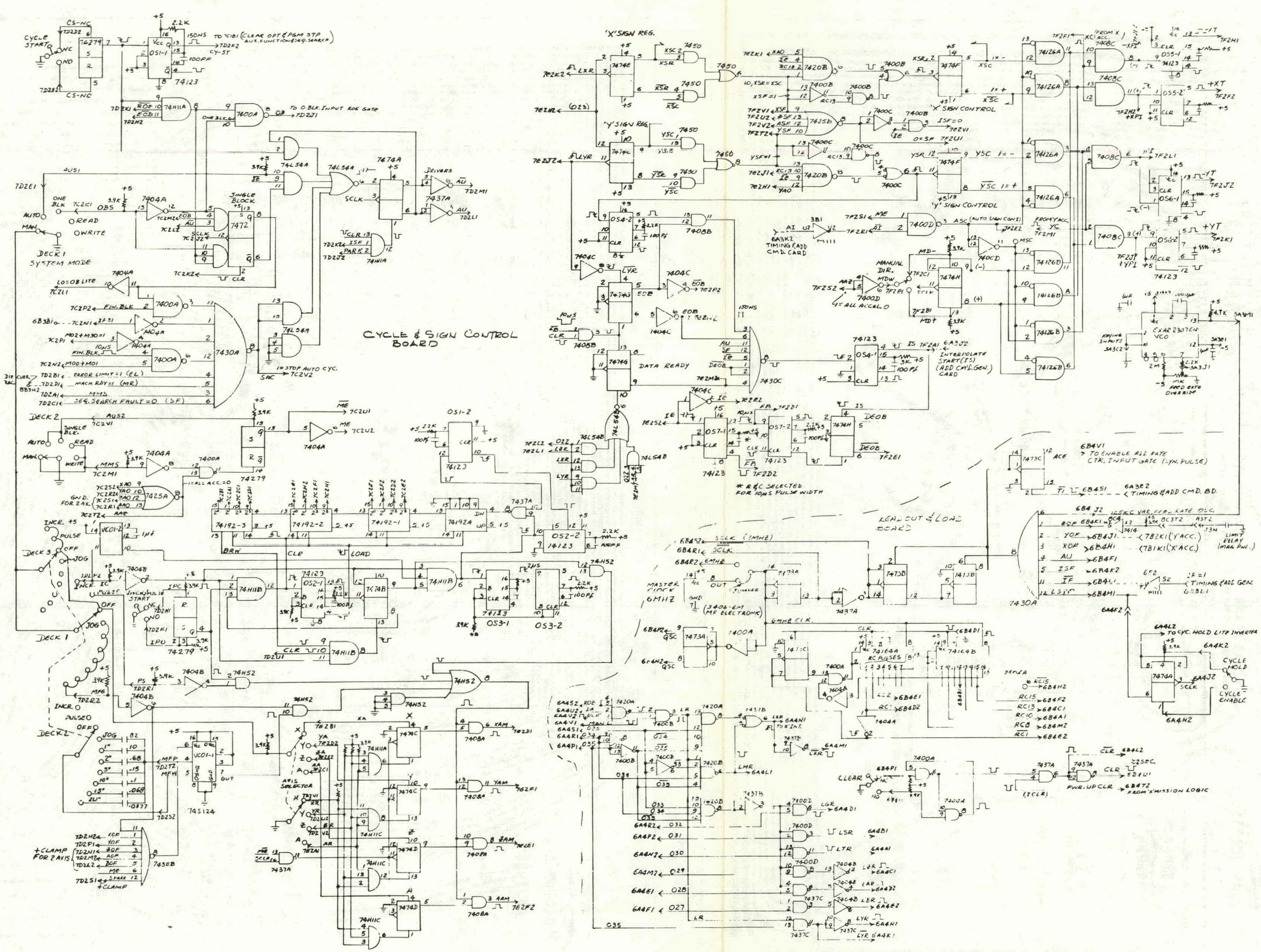


Figure B-25. DIRECT DIGITAL NUMERICAL CONTROLLER. (Cycle-Sign Control Logic)

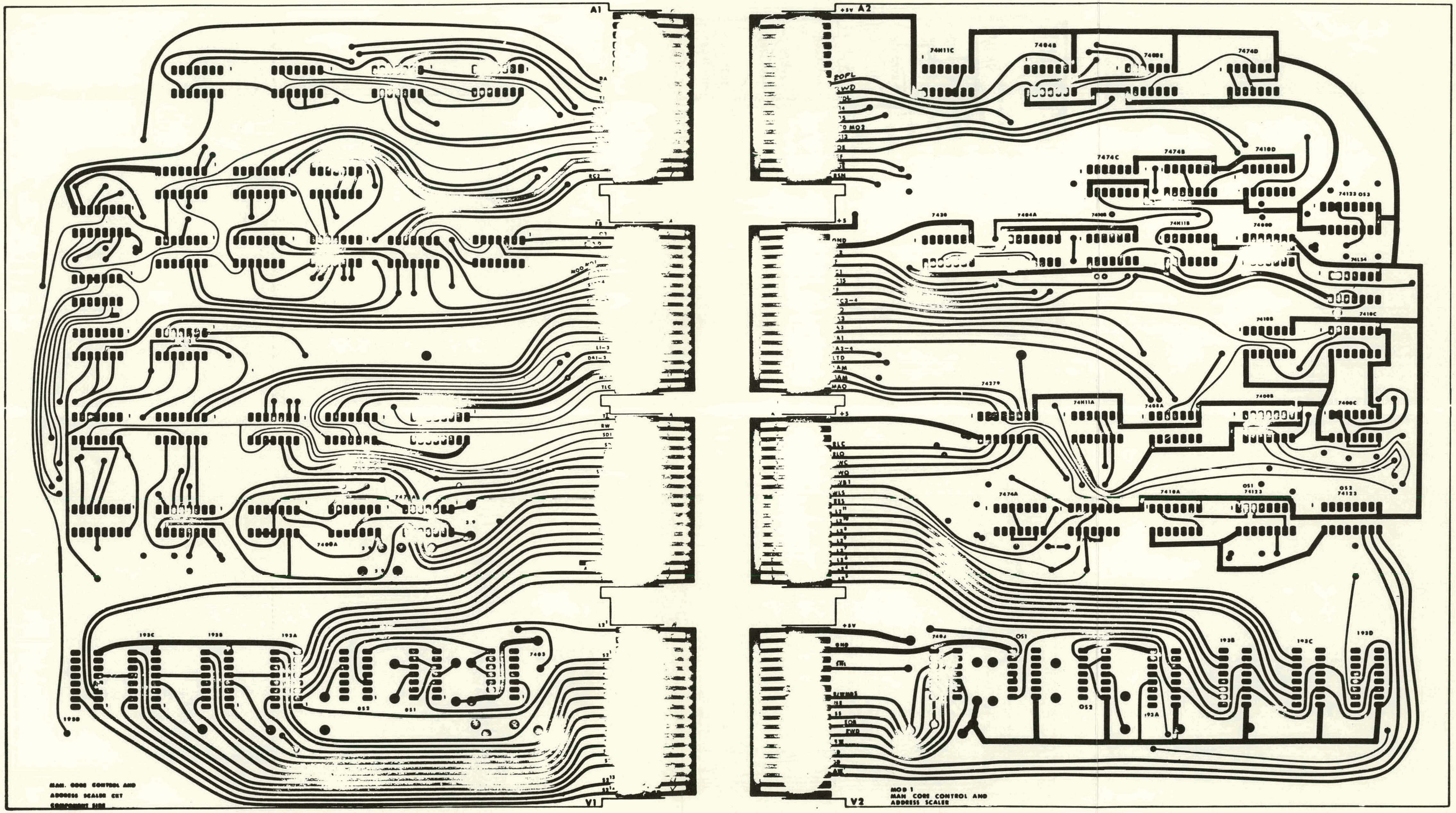
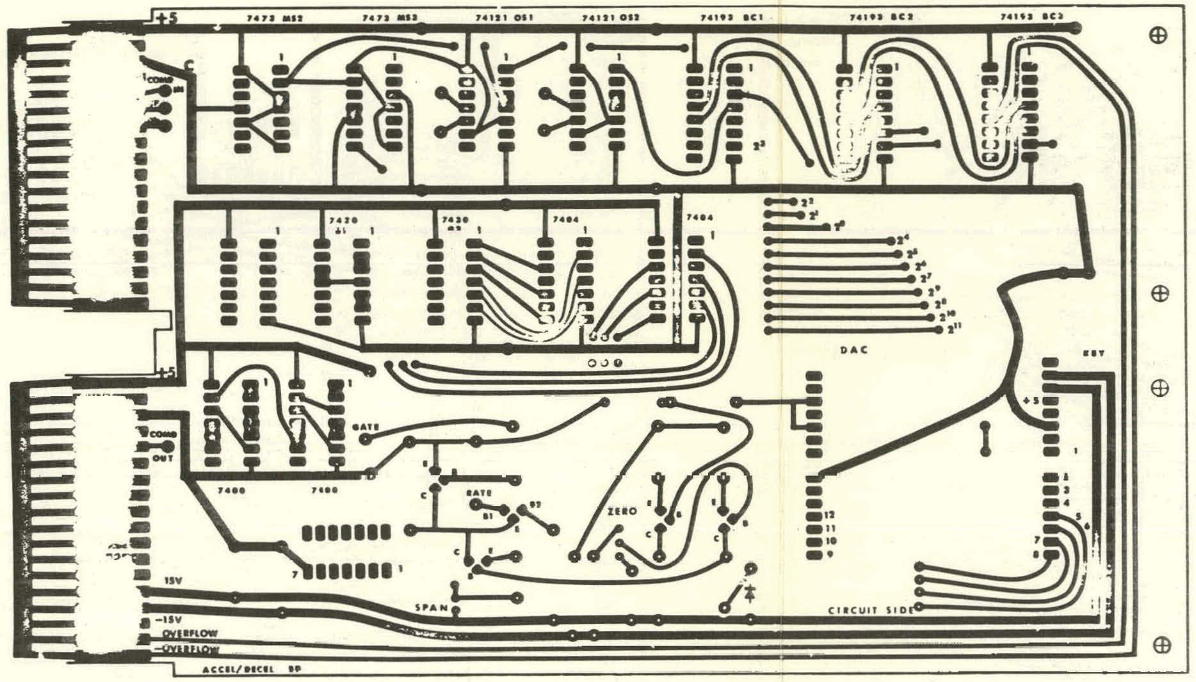


Figure B-26. DIRECT DIGITAL NUMERICAL CONTROLLER. (Manual Core-Address Scaler P/C Layout)



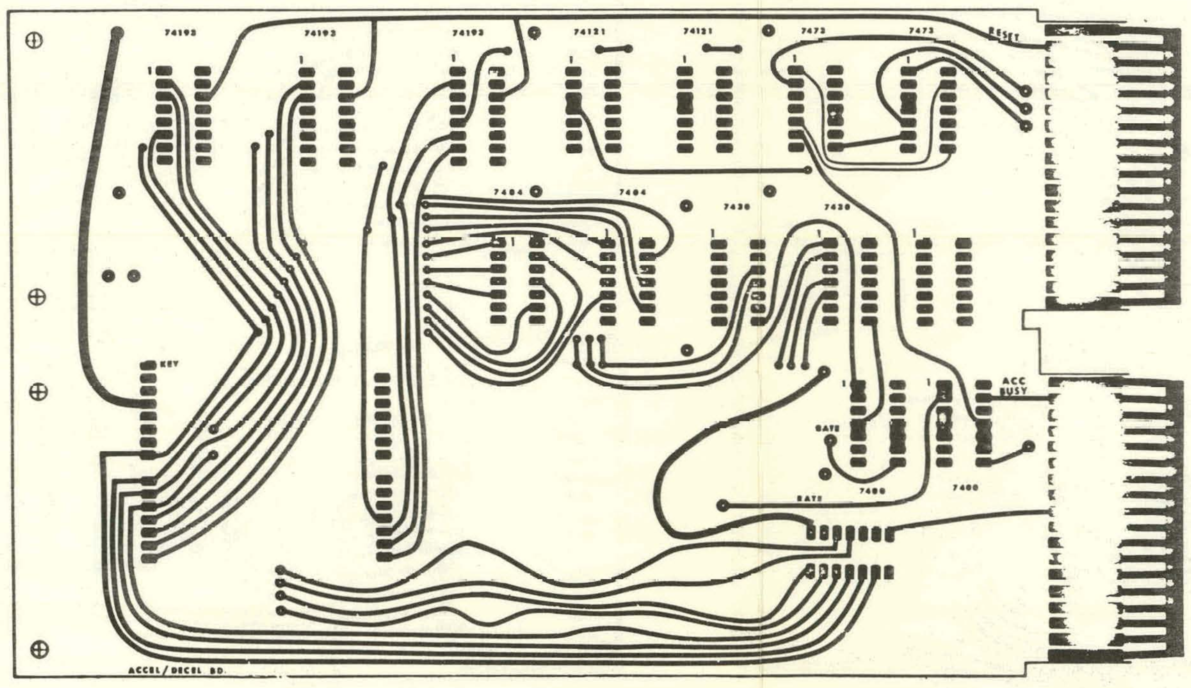
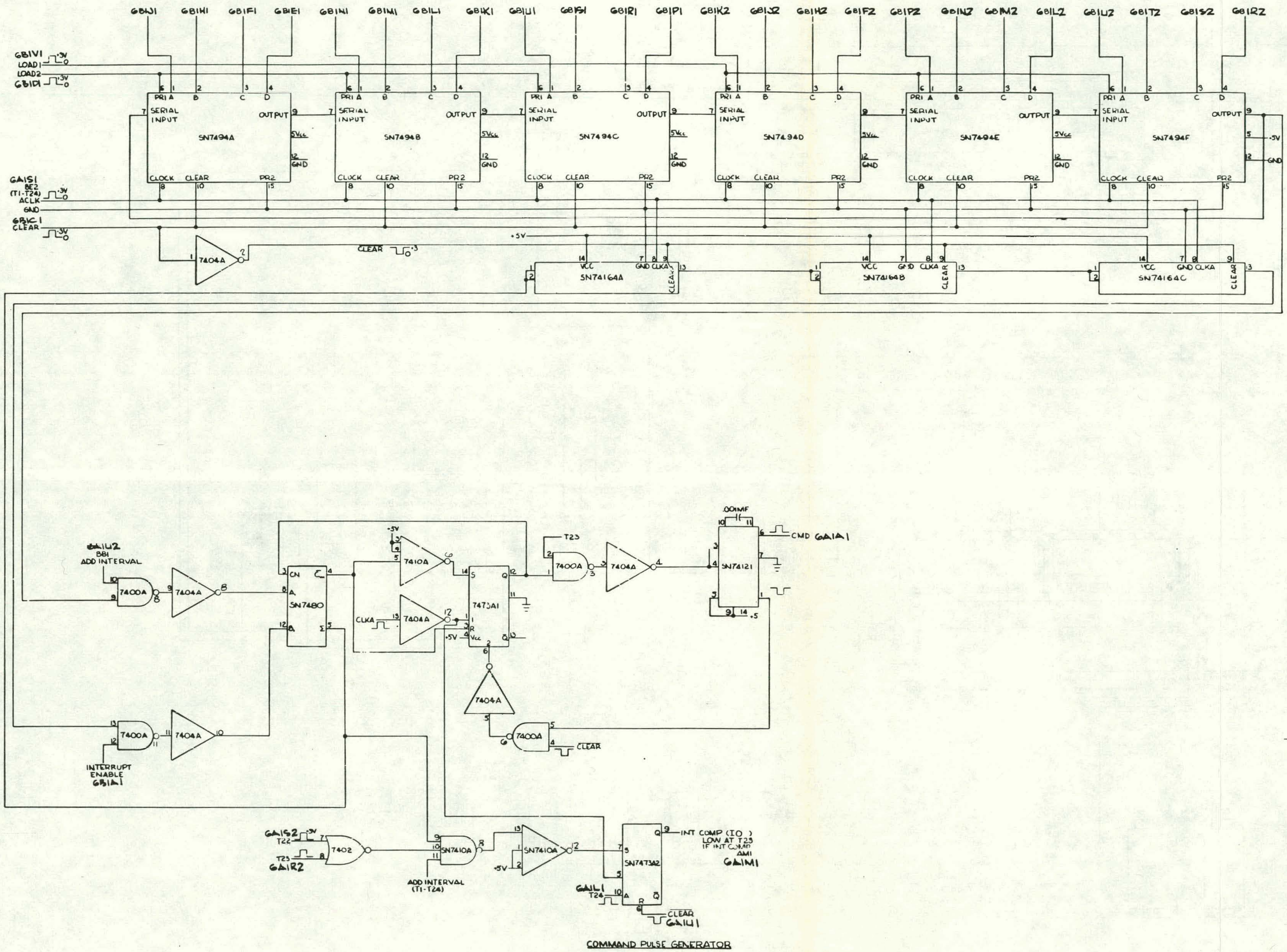


Figure B-27. DIRECT DIGITAL NUMERICAL CONTROLLER. (Acceleration-Deceleration P/C Layout)



NOTES:
1- COMMAND PULSE GENERATOR Y IS IDENTICAL. OCCUPIES SLOTS GA2 & GB2.

Figure B 28. DIRECT DIGITAL NUMERICAL CONTROLLER. (Command Pulse Generator Logic)

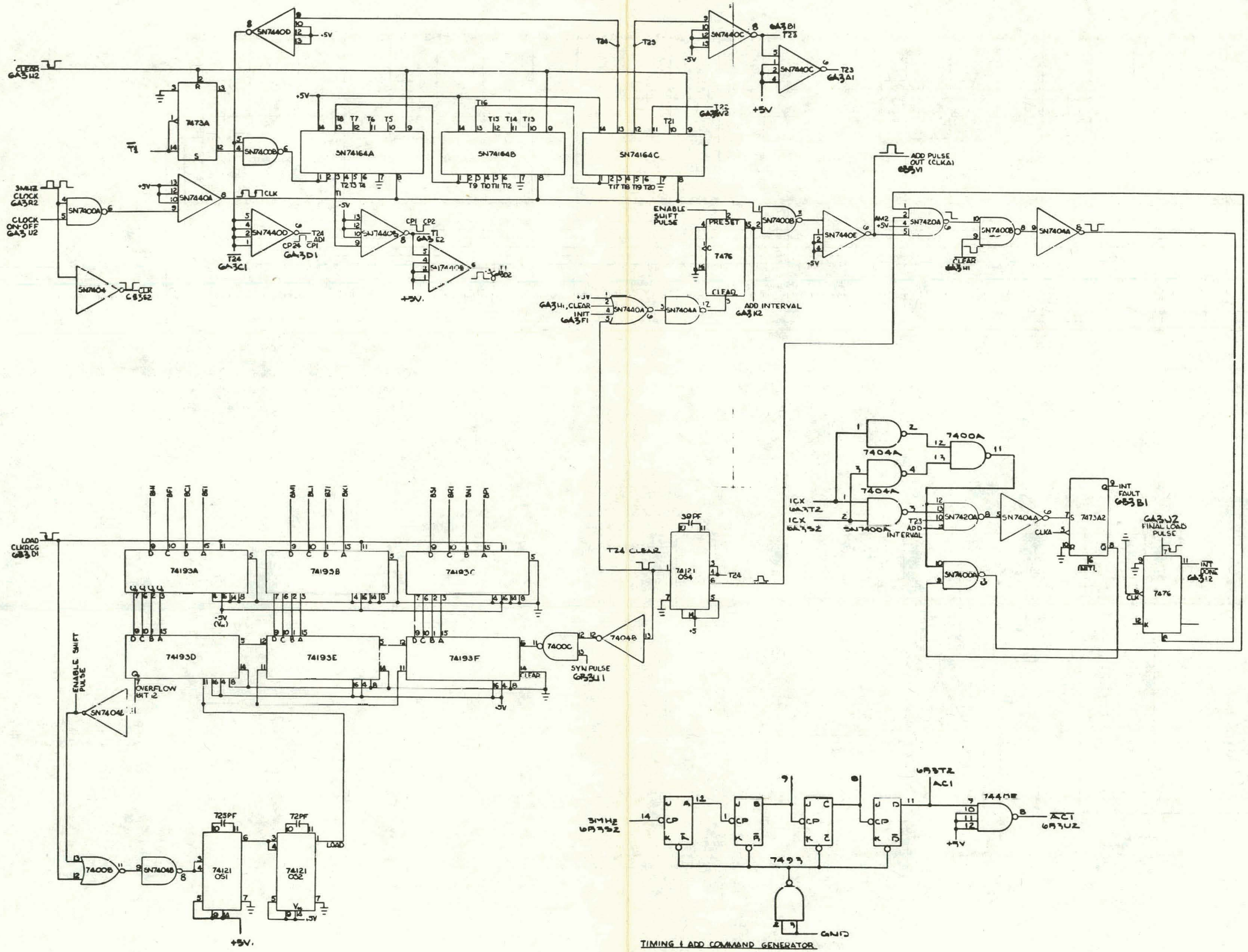
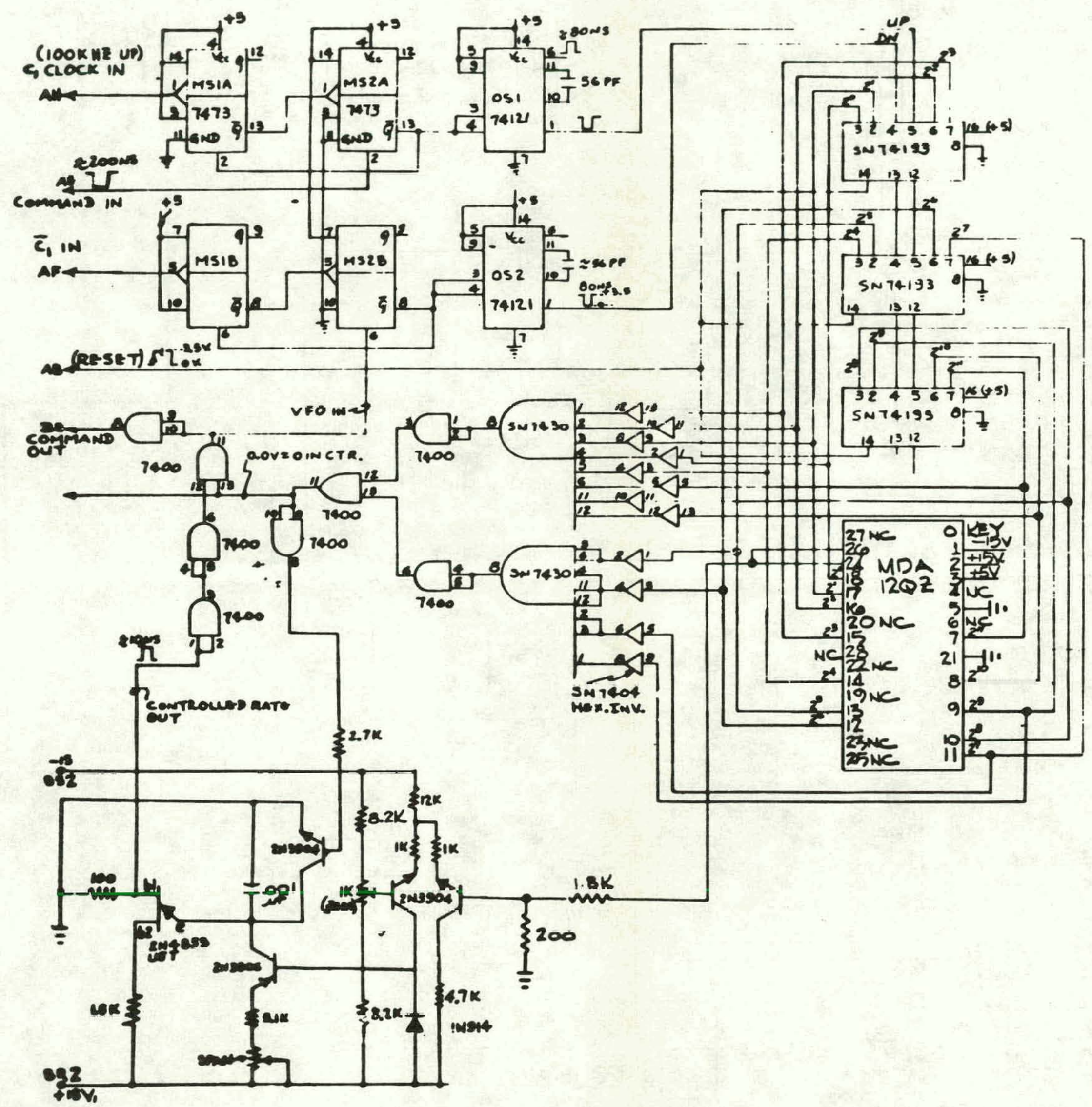


Figure B-29. DIRECT DIGITAL NUMERICAL CONTROLLER. (Time-Add Command Generator Logic)



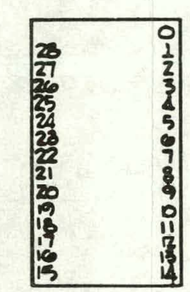


Figure B-30. DIRECT DIGITAL NUMERICAL CONTROLLER. (Auto Accelerator/Decelerator Circuitry)

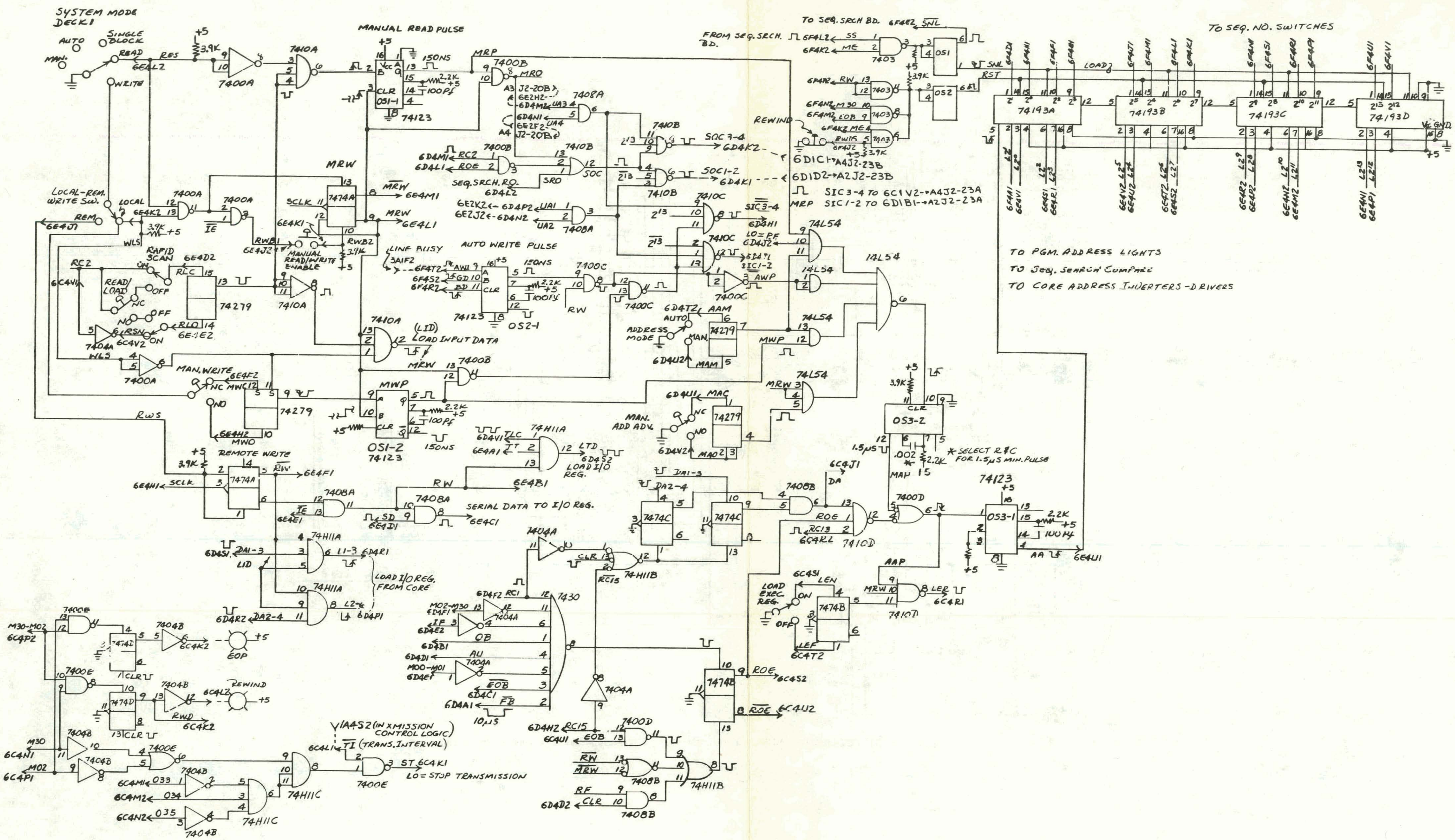


Figure B-31. DIRECT DIGITAL NUMERICAL CONTROLLER. (Manual Core-Address Scaler P/C Layout)

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